# RESIDENTIAL LOAD MANAGEMENT STRATEGY
# FOR LOCAL NETWORK OPTIMIZATION

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## ABSTRACT

This paper investigates how Residential Load Management impacts the power flows and voltages on Distribution Networks, and how the impact could be minimized. The power consumption of LV customers fluctuates a lot, and the summation of their flows results in a flatter curve than each individual curve. Demand Side Response activation orders tend to resynchronize the variation of individual customers. This paper investigates a simple method that each flexibility operator could use to mimic the natural random behaviour of consumers.

## INTRODUCTION

Residential Load Management (or DSR-Demand Side Response) is the process of curtailing the electricity load in a substantial number of installations and especially households for a short period. Since the first activations by the French Transmission System Operator in year 2007, the number of customers involved in this process has significantly raised. Besides, in late 2013, new mechanisms such as "NEBEF" (Notification d'Echange de Bloc d'Energie) were designed in France, to allow more participation of DSR capacities in the energy markets.

When implemented in every household at the same time in the same geographical area, Load Management tends to synchronize the consumers behavior, whereas natural peak attenuation is generally observed in the absence of such external signal. Distributions System Operators (DSO) rely on this phenomenon in order to locally optimize the network resources and fit them to the local needs of customers.

However simultaneous curtailments can cause peaks to appear at the end of the market-based peak shaving event, generally known as rebound effect. When it occurs, such variations may represent up to 20% of the normal load. By disturbing the average statistical peak attenuation observed among consumers, synchronized load management is likely to trigger local electrical constraints whereas these flexibilities can help support the overall system.

Thus, ERDF is developing a simple method to facilitate the integration of most of these flexibilities while reducing new network constraints. It would enable each aggregator to reproduce/mimic the peak attenuation of installations by simply taking into account their geographical proximity and thus the likelihood of belonging to the same low-voltage distribution network.

This method is based on a Round Robin scheduling algorithm using the DSR clients addresses. This article presents how much this method could help to reduce network side effects due to DSR synchronization and the conditions of its efficiency.

## LV DISTRIBUTION NETWORK DESIGN

### ERDF's Design Method of LV Networks

ERDF's design method for LV network is based on a statistical analysis of voltages and currents.
Each customer is assigned to a profile depending on its tariff and type of electrical installation (residential, commercial, industrial). Each profile is based on a load characteristic of 48 points: a 24-point curve for business days and a 24-point curve for weekends. The model includes an average demand curve $m_i(h)$and a variance curve $(\sigma_i(h))$. They can be estimated in different way depending on the types of loads.

The Norton Law is calculated taking into account the desynchronism of the behavior of consumers. The total load is modeled by its average curve and its variance curve calculated as follows:

$$m_{tot}(h) = \sum m_i(h) \quad \text{and} \quad \sigma_{tot}(h) = \sqrt{\sum \sigma_i(h)^2}$$

As a consequence, the resulting power passing through the transformer is usually between 3 to 6 times below the actual sum of each subscribed power. Node voltages, line and transformer currents are finally estimated using a risk coefficient that enables the DSO to cover 90% of the situations (10% of the situations are not covered).

$$m_{tot}(h) + k_{10\%}.\sigma_{tot}(h) \quad \text{(A)}$$

The curve peak values are then compared to voltage thresholds (+/-10%) and thermal constraints.

### Cost of losses

ERDF's total cupper and iron losses are around 1GWh (about 3.5% of the total energy flows). 20% of these losses are located in LV/MV transformers. Knowing that ERDF operates more than 700000 transformers, cupper and iron losses shall both be economically optimized.

The annual cost of losses of a transformer can be estimated as follows:

$$W_{loss} = P_f \times 8760 + \int_{year} P_c(h)$$

Where

$W_{loss}$ : $Annual\ losses\ (kWh)$
$P_f$ : $Magnetic\ losses\ (kW)$
$P_c$ : $Cupper\ losses\ (kW)$
$8760$ : $Annual\ Number\ of\ hours\ per\ year$

## Optimization of the Transformers Rated Power

The DSO has to study various scenarios associating immediate and future expenses in order to compare costs of upgrading a transformer with the ones of enduring over-sized losses over a certain period of time.

In order to determine if a transformer needs to be upgraded, the following inequation is performed. It uses the cost of losses $C_{loss}$, the difference on losses when changing to a new transformer, the duration of the study **N,** and the actuarial rate i :

$$C_{change} < C_{loss} . \sum_{n=0}^{N} \frac{\Delta W_{loss}(n)}{(1+i)^n}$$

Similar economical considerations are used for a new secondary substation. Combined with thermal constraints described in the previous section, transformers loading should be ideally between 80% to 110% of nominal rated power. ERDF uses this range to design its MV/LV Transformers.

## CUSTOMER MODEL DURING A DSR ACTIVATION

The study of individual measured load curves of customers participating to the same curtailment helped to reveal several phenomena that can be seen on the following figure:

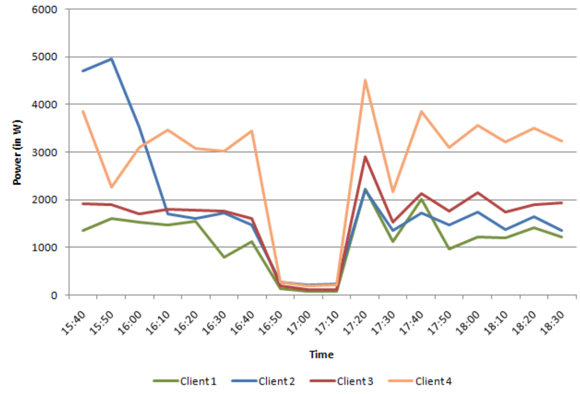


**Figure 1: Measured Load Curves During a Curtailment**

The curtailment happens here between 16:40 and 17:10 where the consumption is reduced to almost 0. At 16:20 a peak occurs due to the compensation of the curtailed energy. Before the curtailment, their behaviors are quite erratic and asynchronous. On the contrary, right after they present synchronous behaviors (local peaks happen at the same time intervals).

Formula (A) in the previous section mimics the peak attenuation. A group of customers is statistically more predictable than each individual and thus its variance is relatively smaller.

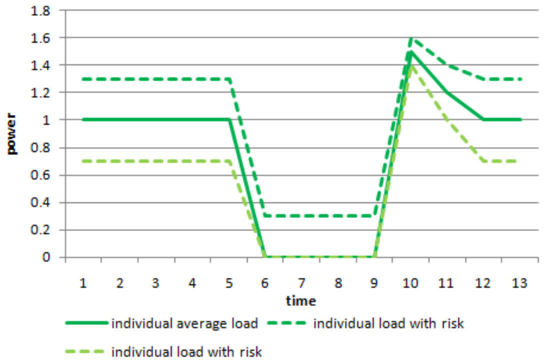


**Figure 2: Simulated Load Curves during a Curtailment**

After a curtailment, the behavior of the customers is less erratic, and part of the load gets synchronized. We thus introduce a synchronization coefficient k. The individual load current becomes:

$$C_i(h) = [m_i(h) + p_{peak\,i} + k.k_{10\%}.\sigma_i(h)] + [(1-k).k_{10\%}.\sigma_i(h)]$$

And total consumption becomes :

$$C_{tot}(h) = \sum_j m_j(h) + \sum_i [m_i(h) + p_{pea\,k_i} + k.k_{10\%}.\sigma_i(h)] + \sqrt{\sum_j \sigma_j(h)^2 + \sum_i [(1-k).k_{10\%}.\sigma_i(h)]^2}$$

$k$ : Synchronization coefficient
$p_{peak\_i}$ : Curtailment energy bounce depending on the duration of the curtailment
$i$ : Customer with curtailment
$j$ : Customer without curtailment
$k_{10\%}$ : Risk ratio (90% of situations are covered)

## STATISTICAL ANALYSIS OF THE IMPACT OF DSR ON A REGION

### Presentation of the scenario

A statistical analysis, on urban LV networks was performed. Urban areas having rather satisfactory loaded transformers (cities usually have enough consumption to economically load the transformers), a high density of DSR consumers can lead to consistent impacts. This panel is over 200 LV networks. Around 14 000 customers are supplied by these networks, mostly private households. The sum transformers rated power is about a third of the total customers subscribed power. For the 200 individual transformers the ratio is between 2 and 6.

$$S_n^{tot} = \sum_{Transformer\ =1}^{200} S_n = 40\ MVA$$

$$P_{suscribed}^{tot} = \sum_{Client\ =1}^{14\ 000} P_{subscribed} = 120\ MVA$$

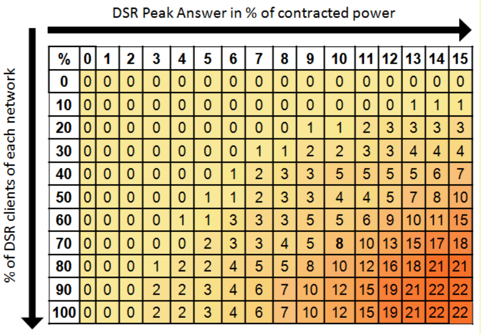
$$\Rightarrow\ P_{suscribed}^{tot} = 3.S_n^{tot}$$

This "smoothing efficiency" is due to the natural peak attenuation of the loads. It allows ERDF to optimize the design of its transformers by a factor 3.

## Analysis and Results

On these networks a statistical analysis of the impact of load curtailment was performed. DSR penetration (ratio of curtailed customers) was taken between 0 and 100%.

**Table 1: Ratio of Networks with thermal constraints as a function of the ratio of curtailed customers and curtailment rebounce amplitude**



DSR Peak Answer in % of contracted power

% of DSR clients of each network

| % | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 3 | 3 | 3 |
| 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 |
| 40 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 5 | 5 | 5 | 5 | 6 | 7 |
| 50 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 3 | 3 | 4 | 4 | 5 | 7 | 8 | 10 |
| 60 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 3 | 3 | 5 | 5 | 6 | 9 | 10 | 11 | 15 |
| 70 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 3 | 4 | 5 | **8** | 10 | 13 | 15 | 17 | 18 |
| 80 | 0 | 0 | 0 | 1 | 2 | 2 | 4 | 5 | 5 | 8 | 10 | 12 | 16 | 18 | 21 | 21 |
| 90 | 0 | 0 | 0 | 2 | 2 | 3 | 4 | 6 | 7 | 10 | 12 | 15 | 19 | 21 | 22 | 22 |
| 100 | 0 | 0 | 0 | 2 | 2 | 3 | 4 | 6 | 7 | 10 | 12 | 15 | 19 | 21 | 22 | 22 |

For each LV networks, 10 x 15 scenarios were studied depending on the percentage of DSR clients on it and the strength of curtailment answer peak. The curtailment energy rebounce varies between 0% and 15% of contracted power.

This shows that 0% of LV networks currently have thermal constraints, this value can rise up to 22% with synchronized curtailments.

## SYNCHRONOUS PACKAGE CONCEPT

Proper transformer design leads to operate transformers close to their maximum rated value. As a consequence the synchronization of customers power consumptions can increase peak power values and have flows reach thermal limits. Several methods are investigated in SmartGrid projects in order to coordinate the activity of flexibility Operators with DSOs. Having in mind the large number of LV customers potentially participating in DSR programs, this coordination could become very demanding in terms of data exchange.

Thus, our objective was to design a simple method that would meet the following requirements. It should:

- Require limited data exchanges between actors,
- Lead to a total load curve that would be as smooth as existing load curves,
- Be simple to implement
- Ensure equality of treatment between all actors.

The principle of this method is as follows (see example in Table 1 :

- Each flexibility actor creates $N_p$ packages of customers. These packages are initially empty.
- The list of customers is organized in alphabetical order of the city, then, street name, then, street number and finally customer name of Id.
- Only customers belonging to the same package are activated during the same time period ( See Figure 3)

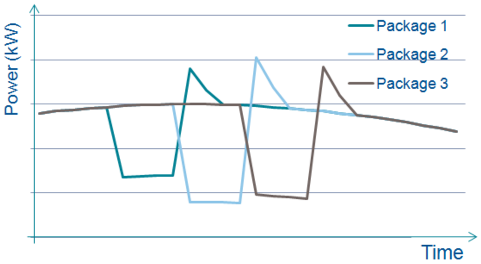


**Figure 3: Load Curve with Three Synchronous Package**

The $N_p$ packages are then populated using a Round Robin algorithm: by going down the list and assigning the package number using a circular permutation. The most common smoothing efficiency being around 3, the standard number of groups can be $N_p = 3$.

This method does not require the positions of the customers installations on the grid, but is quite well correlated with them. Customers living in the same building will be shared between the packages. Likewise, customers living in the same street will be shared between the packages as well.

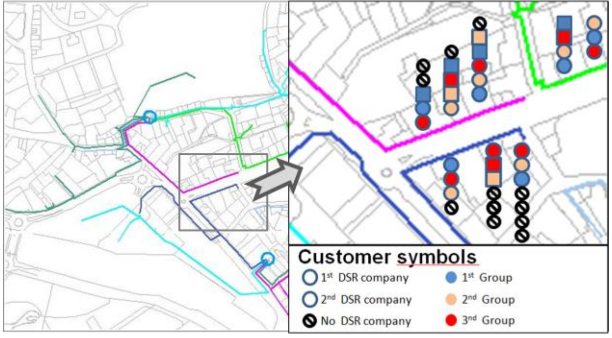


**Figure 4: Example of Round Robin Application of a Street**

**Table 1: Example of Package Population**

| Zip code | Street | St. Number | Cust Id | Package # |
|---|---|---|---|---|
| 34600 | Main St. | 114 | Ms Shanell | **1** |
| 34600 | Main St. | 344 | Ms Lipman | **2** |
| 34600 | Main St. | 344 | Ms Peters | **3** |
| 34600 | Main St. | 380 | Mr Eilers | **1** |
| 34600 | Main St. | 380 | Mr Forgione | **2** |
| 34600 | Market Ave | 230 | Ms Cutshaw | **3** |
| 34600 | Market Ave | 238 | Ms Darcey | **1** |
| 34600 | Market Ave | 238 | Mr Kimball | **2** |

## IMPACT ON A LOCAL CITY NETWORK

### Presentation of the area

The simulation was performed on an urban area. Main Street (located in the middle of the picture) is fed by several transformers. All of them are designed as described earlier, i.e. loaded between 80% and 110% of their nominal rated power.

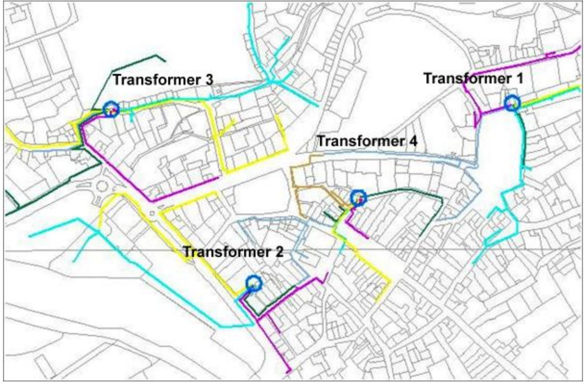


**Figure 5: Area Supplied by the 4 Secondary Substations**

**Table 2: Characteristics of the Transformers**

| Transformer | Nominal power (kVA) | $P^{tot}_{suscribed}$ (kW) | $S^{tot}_{n}$ (kW) | Nb of customer |
|---|---|---|---|---|
| Transformer 1 | 400 | 1933 | 328 | 243 |
| Transformer 2 | 250 | 1268 | 225 | 131 |
| Transformer 3 | 400 | 2010 | 411 | 239 |
| Transformer 4 | 400 | 1891 | 384 | 223 |

### Description of the scenario

The simulation scenario is based on the following conditions:

- 2 different DSR companies present on Main Street,
- 40% of Main Street residential consumers are involved with a DSR program,
- A one-hour curtailment is programmed.

The simulation is made when the transformer is at its maximum load and using the individual loads model described before in the three following situations:

- Without curtailment (our reference),
- With a synchronous curtailment,
- With a 3 packages of synchronized curtailments being activated one after the other.

**Table 3: Transformer Load for Several Situations**

| Transformer | Scenario | Average load (%) | Maximal load with a 90% risk level (%) |
|---|---|---|---|
| Transformer 1 | Without curtailment | 82.0 | 90.4 |
| | With 1 group | 92.2 | 100.3 |
| | With 3 groups | 84.3 | 92.6 |
| Transformer 2 | Without curtailment | 90 | 101.2 |
| | With 1 group | 108.1 | 118.4 |
| | With 3 groups | 94.3 | 105.2 |
| Transformer 3 | Without curtailment | 102.0 | 111.4 |
| | With 1 group | 120.2 | 129.0 |
| | With 3 groups | 106.3 | 115.5 |
| Transformer 4 | Without curtailment | 95.7 | 105.3 |
| | With 1 group | 111.1 | 120.2 |
| | With 3 groups | 99.2 | 108.7 |

The synchronous strategy creates load constraints on three of the transformers (load > 110%) whereas the 3-package strategy reduces the peak by 4 the overload. Using 3 packages reduces the peak by a factor up to 4. When the natural smoothing effect of loads is higher than 3 and the peak is close to rated power, a higher number of packages would theoretically be necessary (i.e. transformer #3).

## CONCLUSION

ERDF designs LV networks by taking both the thermal, voltage constraints and the economical aspect of losses. Because of Iron losses, transformers are better designed when the peak power reaches 80% to 100% of rated power.

A natural peak attenuation can be observed when loads are not synchronized. This enables DSOs to optimize networks and avoid a design method only based on the total subscribed kVAs.

Observation of load curtailments lead us to realize that at the end of the activation, two phenomena happen: a energy rebounce, but also a resynchronization of the customer behaviors.

The paper presents a new method that requires small amounts of data exchanges, limits the impacts on most of networks and aims at being easily applicable for Flexibility Operators. The natural smoothing efficiency of the peak attenuation is around 3 (ratio between the total subscribed power and the transformers rated power), and if each Flexibility Operator uses 3 packages of customers for its curtailment activations, curtailment has no impact on network design.

When the natural smoothing efficiency of the peak attenuation is higher (typically 4 to 6), further investigations are needed to identify appropriate solutions to avoid costly network investments.

Further studies show that this method also improves the impact of voltage levels in balanced conditions. However, this method does not necessarily improve voltage unbalance on LV networks and MV impacts. New studies will be needed to analyze these issues.

## REFERENCES

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