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To cite this version:
Barnabé Potel, Florent Cadoux, Vincent Debusschere, Leticia de Alvaro Garcia. Impact of the Periodicity of Feeder Re-Allocation on the Efficiency of Under-Frequency Load Shedding. 2019 IEEE Milan PowerTech, Jun 2019, Milan, Italy. hal-02166700

HAL Id: hal-02166700
https://hal.science/hal-02166700
Submitted on 4 Sep 2019

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Impact of the Periodicity of Feeder Re-Allocation on the Efficiency of Under-Frequency Load Shedding

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Abstract—When a large generation-consumption unbalance occurs, under-frequency load shedding (UFLS) is the last resort to restore this balance by disconnecting loads from the electrical power system. In France, the UFLS is realized at the level of primary substations by allocating groups of MV feeders to under-frequency relays. Choosing and implementing this allocation requires substantial operator work, and is currently done once a year in France. In the near future, however, it may become both necessary and technically feasible to update the UFLS scheme more frequently; this is the investigated topic of this paper. Firstly, several re-allocation strategies are defined, whose periodicity ranges from months to hours. Then their applications are simulated on a large real-world dataset based on the actual consumption of individual MV feeders from an entire French region over two years. The performance of the various proposed strategies are compared and recommendations regarding the implementation of future UFLS re-allocation methods are provided.

Index Terms—Defense plan; Europe; Frequency relays; UFLS

I. INTRODUCTION

The under-frequency load shedding (UFLS) is the last resort to avoid a black-out due to a generation-consumption unbalance. The frequency of the electrical power system (EPS) is directly linked to this unbalance: when consumption is higher than generation, frequency decreases, and conversely. This is mainly due to the swing equation, characteristic of the synchronous generators. The UFLS is an automatic load shedding mechanism which is designed to stop large frequency drops – the purpose of UFLS is thus not to precisely control frequency, only to react to large deviations that could not be prevented by finer controls such as primary frequency control. Once frequency is stabilized, the secondary reserve and the manual actions of system operators (such as starting-up additional generation or shedding selected loads) bring it back to its nominal value.

In Europe, the latest grid code dealing with the UFLS is the Network Code on Emergency and Restoration (NC-ER) [1]. It requires Transmissions System Operators (TSO) and Distribution System Operators (DSO) to implement a new scheme for the UFLS. A UFLS scheme is currently composed of steps, each of these step being designed to disconnect a specific amount of the load when a given frequency threshold is reached [2], [3]. Other, more elaborate UFLS methods have been proposed in the literature, typically relying on sophisticated measurements such as the rate of change of frequency (ROCOF) [4]–[6] to shed the appropriate amount of load corresponding to the initial unbalance and sometimes even to ensure correct post-UFLS values of power flows and voltage [7], [8]. To the best of our knowledge, these elaborate methods have however not been implemented so far. The latest version of the NC-ER mostly follows the traditional logic based on frequency relays, but also introduces a new option: system operators may implement an additional load shedding mechanism based on ROCOF measurements. This new scheme can however only be applied before frequency reaches 49 Hz; then the traditional UFLS scheme based on frequency-triggered steps must be used.

In France, steps are composed of thousands of under-frequency relays located in primary substations. Each relay disconnects a few MV feeders – whose typical consumption is in the order of a few MW – all over the French EPS. Each relay is set to trigger at one of four pre-defined frequency thresholds, thus constituting four UFLS steps (plus a fifth “step” for the feeders that are not associated with any relay, and thus cannot be shed by the UFLS scheme).

In France, DSOs such as Enedis are in charge of selecting the UFLS step to which each MV feeder will belong; this is what is called the allocation of the feeder. The allocation is currently chosen by first measuring the load of every feeder at a specific date and time, which provides a “weight” for each feeder; and then by manually populating the five UFLS steps with feeders:

- in such a way that the total weight of each step is adequate;
- and according to the nature of their loads (residential, industrial...) in order to reduce the impact of load-shedding on the industry [9].

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The work reported in the paper has been developed in the framework of the Enedis Industrial Research Chair on Smart Grids.
In practice, a coefficient – defined in Section III-A – based on the number of MV and LV customers is used to determine the more or less “industrial” nature of each MV feeder. The allocation process is realized manually by operators, once a year, in every region of France.

In this paper, the traditional UFLS logic based on frequency relays is kept, but it is assumed that updating the allocation can be automated and thus be made more frequently; this assumption is true for modern primary substations that use digital supervision and control technologies, and false for older substations that use legacy technologies.

In addition, this paper considers alternative allocation methods where the “weight” of a feeder is not defined as its consumption at a specific date and time, but as another indicator: the mean consumption of the feeder over a certain period of time, as defined in Section III-C, is used.

The core of this paper is thus the proposition and characterization of simple methods to realize the feeder allocation using a shorter periodicity, from few hours to one year, possibly using alternative ways to define the notion of “weight” for a feeder. These allocations are tested with the data provided by Enedis: the consumption of all the feeders of a French region over two years.

II. SCHEME TO IMPLEMENT

A. NC-ER requirements

The NC-ER imposes new requirements to design the UFLS scheme. The scheme proposed in Table I is one of the compliant schemes regarding the national system. The most restrictive requirement is the total load to shed which has to remain close to 45% of the national consumption [1].

The second part of Table I represents the objective scaled at the distribution system. In the French EPS, load shedding is realized only in the distribution system [9]. The latter comprises around 75% of the total national load. Thus, the TSO, responsible for the load shedding, imposes a ratio to shed to the DSOs. In this study, the ratio that the DSO has to shed is considered to be 60% of its system – which is 45% divided by 75%.

In practice, the UFLS scheme is subject – like any protection plan – to non-idealities such as tripping delays, measurement inaccuracy of the under-frequency relays, faulted relays, etc. As a consequence, when the UFLS activates, not all the relays that were theoretically allocated to a given step actually trigger; a fraction of the relays do, and the other do not [10], [11]. Because of these possible variations in the shedding of the steps, in the next sections the results are shown mainly using the performances of the total allocated consumption.

The objective to shed can be written such as:

$$ R_{\text{obj}, t} = \alpha \times c_{R_t} $$

$$ c_{R_t} $$ is the consumption of the considered region R at time t.

$$ \alpha $$ is the ratio to shed, here 60% for the cumulative allocated consumption of the distribution system.

<table>
<thead>
<tr>
<th>Step</th>
<th>Frequency (Hz)</th>
<th>Cumulative (%)</th>
<th>Cumulative (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>49</td>
<td>7.5</td>
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<tr>
<td>2</td>
<td>48.8</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>48.6</td>
<td>7.5</td>
<td>22.5</td>
</tr>
<tr>
<td>4</td>
<td>48.4</td>
<td>7.5</td>
<td>30</td>
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<tr>
<td>5</td>
<td>48.2</td>
<td>7.5</td>
<td>37.5</td>
</tr>
<tr>
<td>6</td>
<td>48</td>
<td>7.5</td>
<td>45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shed load (%)</th>
<th>National system</th>
<th>Shed load (%)</th>
<th>Scaled to the distribution system</th>
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<tbody>
<tr>
<td>10</td>
<td>10</td>
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</tbody>
</table>

$$ R_{\text{obj}, t} $$ is the consumption to shed at instant t of the region $ R $. The allocated consumption is defined:

$$ \text{allocated consumption} = \frac{\sum_{f \in F_R} c_{f_t}}{c_{R_t}} $$

$$ F_R $$ are the allocated feeders in region $ R $.

$$ c_{f_t} $$ is the consumption of the feeder $ f $ at instant $ t $.

The goal is that the allocated consumption, here in $ p.u. $, is the closest possible to the objective to shed at every instant of 60% $ = 0.6 p.u.$.

B. Data and objective

The objective defined in (1) is the real objective at each time. Nevertheless, when allocating the feeders, their consumption is not known in advance. Thus, feeders are allocated according to their historical consumption.

The data which is used correspond to the consumption of 858 feeders over years 2014 and 2015, with a time-step of 30 minutes. These 858 feeders compose a French administrative region whose the total mean consumption is $ \sim 1.3 $ GW.

As example, the consumption of feeders over the year 2014 are used to determine their allocations for the year 2015, then performance over the year 2015 is checked.

III. METHODS OF ALLOCATION

A. Principle of re-allocation

Historically, the allocation of the feeders is done once a year in the French EPS. This allocation has two purposes:

1) To reassess the weight of load that has to be shed;

2) To add or remove specific feeders about how critical they are (composed of loads such as hospitals, government places, street lighting, etc).

In term of the weight of the load, the use of the mean consumption of the feeder over the allocation period is considered in this paper. Nevertheless, it gives a lot of possibilities of feeders combinations to reach the 60% of consumption to shed. To limit these possibilities, what the French DSO Enedis calls the $ K $ coefficient is implemented.

This coefficient is defined in order to arrange the feeders according to the type of loads they are composed. The idea is to shed, firstly, the feeders composed mainly by residential consumers (LV customers) instead of industrial customers.
present on the medium voltage. This coefficient was defined with the aim to reduce the impact of load-shedding on the industry, which has a direct economic impact.

Other authors proposed the use of another coefficient based on the insertion of the photovoltaic generation [12] to avoid the shedding of mixed feeders whose power flow comes back to the substation and will worsen the unbalance.

The steps are created using this coefficient: the first steps are composed by the feeders with the less priorities as the last steps are composed by the feeders with higher priorities.

### B. Motivation for shortening the periodicity of re-allocations

The allocated consumption, represented by the sum of the consumption of the allocated feeders, may have large variations. This is due to the consumption profile of the load of which they are composed: some will have higher consumption during winter (residential with electrical heating), others may have important consumption during working days (businesses, industries), etc. The purpose of shortening the periodicity of re-allocation is to mitigate these variations. Fig. 1 illustrates the principle of lower allocation periods: to “force” the mean value of the allocated consumption over the allocation period to be closer to the objective to shed (60% = 0.6 p.u.).

Whether increasing the allocation frequency will reduce the deviation of the allocated consumption or not is directly linked to the “temporal repeatability” of the consumption used to realize the allocation. Forecast models to improve the performances of the allocation are not exploited. But, in the next part, two simple methods which are straightforward to implement and based on historical data are used.

### C. Methods

Two methods are compared. The difference between them is the forecast consumption. The first method is based on the assumption that the whole consumption of the previous year will repeat; while the second method uses the consumption of the previous allocation period only – which can vary from one year to few hours.

For example, considering an allocation period of 1 month:
- Method 1 determines the allocation for a certain month of 2015 considering the data of the same month of 2014.
- Method 2 determines the allocation for one month considering the data of the previous month. E.g. consumption of March 2015 is used to do the allocation for April 2015.

The idea of using these two methods is to take into account specific variations of the consumption over the time: if the allocation period is one day, taking the consumption of the same day but one year before is not relevant (method 1), it is more relevant to take the consumption of the day before the considered day (method 2). On the contrary, for an allocation period of a few months, it could be interesting to take into account seasonal variations of the allocated consumption of the previous year (method 1).

It allows to determine what is this critical allocation period where the seasonal variations are as important as the changes in the consumption.

### IV. Performance assessment

In this part, the two methods are computed with the data set of the consumption of the 858 feeders. First, various allocations periods are tested with the first method to give an insight of the performances. Then, the two methods are compared to determine the benefits of each methods and in which case it is better to implement one instead of the other.

#### A. Focus on the first method

For the first method, three allocation periods are compared: one-year, four-months and one-month.

1) **Allocated feeders**: the number of allocated feeders varies according to the allocation to respect the mean objective to shed. Table II shows the variations of the number of allocated feeders over a year with the three allocation periods considered.

As the $K$ coefficient is used to determine which feeders has to be allocated as a priority, a difference in the allocated feeders numbers means an addition of new feeders or a subtract of the less priority feeders but it also means the subtract of mixed feeders whose power flow is now feeding back to the substations.

For example, for the 4-months allocation period, the change between 461 to 480 allocated feeders corresponds to:
- 26 feeders added
- 7 feeders removed
- 80 feeders with change in the step

The seven feeders removed correspond to mixed feeders whose weight becomes negative. Fig. 2 shows the – 1-week averaged – consumption of two feeders over the year 2014.
Feeder 200 is only consuming power and keep a mean consumption value comprised between 1.5 MW and 4 MW. The feeder 757 is a mixed feeder whose distributed generation (DG) insertion is such that its consumption reaches negative values: the power-flow is going back to the substation. Its power consumption is comprised between -2 MW and 4 MW depending on the considered period. When this feeder weight is negative, it is not allocated while it may be allocated when this weight is positive.

Thus, the DG has a real impact on the allocated consumption and the weight chosen – here the mean value.

It can be noted that the smaller the allocation period is, the smaller, in this case, the number of allocated feeders are: using a smaller period limits the impact of DG and selects feeders whose power flow is, a priori, not feeding back to the substations. Using larger allocation periods increases the risk to allocated mixed feeders whose weights are lower than non-mixed feeders.

2) Example of the one-month allocation period: Fig. 3. shows the allocated consumption of the one-month allocation period for the year 2014 where the various allocations are calculated and for the year 2015 where these allocations are tested. Due to plotting purposes (high intra-days variations), the allocated consumption are averaged considering a one-week period.

As expected, for the non-causal allocation over the year 2014 the mean value of the allocated consumption between two allocation instants are equals to the objective of 0.6 p.u. to shed. Moreover, this consumption is varying between 0.59 and 0.61 p.u., which can be considered as small variations. When these allocations are applied during the next year, it shows larger variations: from less than 0.56 p.u. to almost 0.62 p.u. (these values are calculated with the one-week average, thus, they differ from the extreme values shown in Fig. 4).

Two aspects of the allocated consumption need to be considered: the spread of the allocated consumption, i.e. its variations, and the mean value of the allocated consumption. The goal is to have a mean value close to the objective (0.6 p.u.) with the smaller variations possible around this value.

3) Comparison between one-month, four-months and one-year periods: density probabilities of allocated consumption on the year 2015 for these periods are shown on Fig. 4.

On this figure it may be seen the two aspects defined previously: for a one-year allocation period, the mean value of the allocated consumption is 0.604 p.u., which is close to the objective of 0.6 p.u. but its variations are important. On the contrary, for the one-month allocation period, the variations are smaller but the mean value is now 0.589 p.u. Fig. 5 shows the decomposition of this allocated consumption by the six steps (which objective to shed is 0.1 p.u.).

The relative variations of the steps are higher than the relative variations of the total allocated consumption – the aggregation of the steps compensate some of their internal variations. As in the Fig. 4, density probabilities can be determine by their variations and by their mean consumption. Here, the first step has large variations but its mean consumption is close to the objective of 10% while the step 3 has lower variations but a mean consumption close to 9.5%.

What compromise system operators would prefer, large vari-
B. Comparison of the two methods

In this section, the performances of the two methods are compared to determine which one is better regarding the period of allocation. To compare the performances, the following key performance indicators (KPIs) are used:

- The standard deviation provides an indication of the internal variations of the allocated consumption.
- The mean error provides an indication of the offset to the objective to shed.
- The root mean square error (RMSE) is a mix indicator of the two previous ones: the quadratic error to the objective.

These indicators are computed for both methods and for allocation periods ranging from 1 hour to 1 year. The results are shown in Fig. 6. An allocation period of one year gives the same results for both methods, as they are identical in this particular case.

The standard deviation and the RMSE are similar for the second method. The difference for the first method is due to the mean error increasing while the allocation period is decreasing. Actually, the mean error evolves in a significant way for the first method compared to the second done.

1) The mean error: is decreasing for the first method, while reducing the allocation period. This is due to an overfitting, which is realized over a shorter period of the previous year. Thus, internal compensations of load variations are less likely to happen. As in Table II, a mean number of allocated feeders for one-month allocation period is lower than the mean number for the four-months period which is lower than the one-year period. The fact that the mean error is negative in this case is due to the differences between the consumption of the more priority feeders from year 2014 to year 2015. In other cases, the mean error could be positive according to the residential and industrial evolution of the consumption.

For the second method, the allocation period has no real impact on the mean error: as the previous period is used to determine this one, this forecast is quite robust. Nevertheless, the standard deviation is more impacted for this method for the important allocation periods (~months).

2) The standard deviation: for the first method is lower than the one of the second method if the allocation period is higher than a month. It means, if the DSO plans to reallocate every month, the use of the data of the previous year (first method) is a better estimation of the variations of the allocated consumption, due to a seasonal variations. On the contrary, if the allocation period is lower than a month, it is more interesting to take the data of the previous allocation period (second method) for the allocation, due to the consumption cycle of different customers.

For the second method and allocation periods of several months, the mean error is close to zero while the standard deviation reaches high values. It is due to the computation of the KPIs over the entire year. For example, with a 6-months allocation period, it shows large mean errors when considering only the first six months of the year or the last six months of the year. These mean errors are compensated regarding the whole year but they lead to an important standard deviation.

With this second method, using an allocation period between two and six months gives reduced performances compared to a one-year allocation period: the seasonal variations are worsen variations of the allocated consumption. As example, if the allocated feeders are mainly composed of residential consumers – due to the K coefficient – their weights will be...
Considering the RMSE cators to take into account these means errors and variations.

3) The RMSE: this indicator mixes the two previous indicators to take into account these means errors and variations. Considering the RMSE, the first method is more relevant than the second one for allocation periods greater or equal to two-months (and not one-month considering only the standard deviation).

Moreover, both methods show a limited interest for a small allocation period:

- The first method shows a minimum in the RMSE for a three-months allocation period. Afterward, the RMSE is increasing while the allocation period is decreasing due to the mean error.
- The second method has a minimum standard deviation matching with the minimum allocation period: the smaller the allocation period, the better the forecast consumption. Nevertheless, a one-week allocation period shows the same performances than a one-day allocation period, and for the considered study, the four-hour allocation period worsen the performances.

Finally, both methods allow reducing the variations of the allocated consumption by reducing the initial allocation period of one year. The performances reach a maximum for the first method considering few months of allocation period, reducing this period is not relevant for shorter allocation periods as there is an over-fitting of the allocation on the variations of the previous year. The second method shows its performances increasing while the allocation period is decreasing. Nevertheless, as the intra-day variations are substantial, it is not relevant to consider an allocation period lower than a week with this method. Overall, for a period higher than one month, the first method gets better results, while for a period lower than one month, the second method is better.

V. CONCLUSIONS

In this paper, the benefits of updating the UFLS scheme more frequently – namely, of shortening the periodicity with which MV feeders are re-allocated to UFLS steps – are studied. This improvement would reduce the gap between the theoretical and the actual weight of an UFLS step, and thus help meet the stringent weight targets that are imposed by the NC-ER. Two simple methods are introduced to realize these frequent re-allocations and the application of these methods is simulated on a large real-world dataset. Relevant KPIs are also introduced to compare the methods, such as the RMSE of the gap between the objective and the actual weight of an UFLS step. The first method consists in taking the consumption data of the previous year to realize the allocation. This method is most efficient with an allocation period comprised between 2 and 4 months. The RMSE is then reduced by 20% compared to the one-year allocation period, which is a substantial improvement of the performance of the allocation. This method is, additionally, straightforward to implement by the operators as the allocation periods of a few months are manually achievable by technicians with the current technology of under-frequency relays – for the considered region only about a hundred operations on the feeders is needed to adapt the allocation.

The second method consists in taking the data of the previous considered allocation period. This method is proved more efficient with shorter re-allocation periods, although under a month, a change in the technology of the relays is required. The use of this second method, using a one-week allocation period, made it possible to improve performance even further over the first method: the RMSE was shown to decrease by 30% compared with the current standard of a one-year period and even 40% considering a few-hours allocation period.

In conclusion, to improve the performances of the allocated consumption, the first thing to do would be to choose which feeders should be allocated considering the consumption profile of each feeder. To go further, the technology of the under-frequency relays may be upgraded in specific parts of the EPS, where the power-fluctuations are the most important, to reallocate them more frequently. In these critical parts of the EPS, the use of more sophisticated algorithms to control new technology relays may help mitigating other issues such as voltage or power-flows limitations when load shedding occurs.

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