EVALUATION OF FLEXIBILITY VOLUMES FOR CONSTRAINT RESOLUTION IN LV DISTRIBUTION NETWORKS – THE NICE SMART VALLEY CASE

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ABSTRACT

This paper presents a study performed by EDF R&D for Nice Smart Valley (NSV), the French demonstrator of the INTERFLEX European project. The study consisted in an evaluation of the impacts of several consumption and generation penetration scenarios on low voltage network constraints and on their leverage feasibility using flexibilities. In a future scenario of evolution in the integration of photovoltaic (PV) generation and electric vehicles (EV), and electricity end-use, we provide an illustration of what constraints may occur in 9 "real-world" LV distribution networks from Nice, France and its surroundings for 20 test days. We then evaluate the potential flexibility that could be used to solve these constraints. Three different evaluation methods are presented. One method is based on a mathematical optimisation, and the other two are based on heuristics with different rules related to flexibility use. Test results on the networks show the effect of the aforementioned evolutions on the potential constraints in these networks and the flexibility that could solve these constraints. This study shall be considered as the first step towards more complete analyses on the subject; it already shows interesting technical results on the flexibilities volume optimization methods.

INTRODUCTION

Electric distribution networks are undergoing many changes: the increasing integration of renewable energy generation and electric vehicles, and the evolution of electricity end-use. Low-Voltage (LV) networks are at the frontlines of these changes. While Enedis (the French DSO) has deployed intelligent monitoring and control at the medium-voltage (MV) level, relatively little has been done at the LV level. LV networks thus do not have monitoring and control infrastructure today even though LV networks are predominantly at the frontlines regarding new electricity usages, flexibilities capability and PV penetration. They are, however, built according to certain robust planning criteria to ensure a good quality of service without constraints.

However, in the future, as these evolutions continue their upward trend, LV networks could present constraints. The INTERFLEX European project [1] and its French demonstrator project Nice Smart Valley (NSV) [2] aim to study interactions between flexibilities and DSOs at the LV level in this future context. A requirement for this is the evaluation of the potential need for flexibilities in this context. To this end, EDF R&D performed an illustrative study on several real-world LV networks for 20 test days, with a projection for the year 2035.

We simulate network conditions in a set of real-world LV networks in the PACA (*Provence-Alpes-Côte d'Azur*) region for these days. The future context of high renewable energy and electric vehicle integration has evidently to be taken into account when network conditions are simulated. The study then aims to develop different methods, based on mathematical optimisation procedures or heuristic rules, to evaluate the flexibility necessary to potentially solve any constraints that may occur in these networks. The main objectives of the study are therefore to:

1. Provide an illustration of constraints in the chosen LV networks under the evolution in production and consumption in the future context, for the defined test days.
2. Evaluate the potential flexibility that could solve these constraints, when different rules are imposed with respect to their utilisation.
3. Perform an analysis of the flexibility evaluation methods used on the resolution of these constraints.

ENTRY DATA AND PRE-TREATMENTS

The major data used in the study were provided by Enedis and / or modelled by EDF R&D:

1. A set of 9 real-world LV urban and rural distribution networks located in Nice and its surroundings. These networks were chosen according to different criteria established in concertation with the NSV project.
2. Consumption data / models for consumers in these networks for a set of 20 test days in the year (30' resolution). This illustrative set of days was chosen across seasons, in concertation with Enedis.
3. PV production profiles for the test days.
4. A future scenario for the PACA region for the year 2035, establishing the expected evolutions in consumption and production in the region, and consisting of the following information on a regional / district / city level:
    a. The expected PV penetration rates
    b. The expected penetration rates of EVs, and
    c. The expected evolution of electricity end-use

The scenario information for 2035 was available at a macro-level. Various pre-treatments were therefore performed on this information to incorporate them into the test networks and get them ready for tests.

From this scenario, a quasi-random allocation and placement of new PV installations on the test networks was done based on a probability distribution of PV installation capacities in France constructed from real-world data [3]. For installed PV, the maximum (PVMax) and minimum (PVMin) production envelopes were considered for tests.

New EV charging points were allocated to networks using scenario data and apportionment techniques. Their consumption was determined using probabilistic consumption models developed by Enedis. Three types of EVs (residential, commercial and car-sharing) with varying capacities, and four types of charging points (residential, commercial, public car-sharing and public non car-sharing) are modelled. The consumption models take into account the different characteristics of these EVs and charging points.

It has to be noticed here that due to modularity efforts in the developed modelling structure other evolutions in consumption can, however, be considered as the scenario contains macro-level information for these evolutions thus enhancing the tolls evolutivity for future more complex studies.

FLEXIBILITY EVALUATION METHODS

Three different methods to evaluate flexibility volumes were developed as a part of the study. They were tested on the LV networks presenting constraints on the 20 test days and illustrate flexibility volumes that could solve these constraints. We do not make any suppositions regarding the real availability of these flexibilities and their monetary value, or compare our solutions against other potential solutions to these constraints.

The developed methods are complementary as they make varying theoretical hypotheses regarding the availability and limits of flexibility at each node in the network. Further, their approaches (optimisation or heuristic rules) differ and can therefore provide a variety of additional information for analysis.

Optimal Reference Method

The Optimal Reference Method is based on a mathematical optimisation. The main hypothesis made in this method is that three-phase flexibility is available in all phases at all consumption nodes in LV networks. The objective is to solve network constraints while minimising the necessary flexibility $FlexP$ across all nodes $i \in C$, time periods $t \in T$, and phases $\Phi = \{A, B, C\}$ of the network.

$$\min \sum_{i \in C} \sum_{\varphi \in \Phi} \left| FlexP_{i,t,\varphi} \right|$$

At each node, the net consumption of active power is expressed as the net difference between the consumption ($Load$), the production ($Prod$) and the flexibility ($Flex$). The load and the production are parameters known beforehand through the different consumption and production data established for the test. The flexibility that can be used in each node and phase is a decision variable limited by an upper and lower bound.

$$P_{i,t,\varphi} = Load_{i,t,\varphi} - Prod_{i,t,\varphi} - FlexP_{i,t,\varphi}$$

$$\underline{FlexP}_{i,t,\varphi} \leq FlexP_{i,t,\varphi} \leq \overline{FlexP}_{i,t,\varphi}$$

The corresponding reactive power values are calculated using the conversion factor $\tan \emptyset$. This is set to 0.4 for loads, 0 for EV charging points, and 0.4 for flexibilities.

A non-linear load flow routine is used to calculate the magnitude of voltages ($v_{i,t,\varphi}$), currents ($I_{ij,t,\varphi}$) and apparent power flow through the transformer ($S_t^{transfo}$). The optimisation sets the values for $FlexP_{i,t,\varphi}$ based on whether or not each of these values conform to their respective bounds:

$$\underline{v_i} \leq v_{i,t,\varphi} \leq \overline{v_i} \;\Big|\; \left| I_{ij,t,\varphi} \right| \leq \overline{I_{ij}} \;\Big|\; S_t^{transfo} \leq S_{max}^{transfo}$$

This method provides a reference optimal value for flexibility volumes necessary to solve LV network constraints. This value can be used as a base on which the two other heuristic methods can be benchmarked. However, the global optimality of this value cannot be guaranteed as the problem is non-linear and non-convex.

Exhaustive Flexibility Placement Method

This method uses heuristic rules to find the volumes of flexibility that could solve constraints. Three-phase flexibility is considered to be available in all phases at all consumption nodes. Additional rules on flexibility use are imposed depending on the type of constraints.

If a feeder is constrained, only one flexibility, present anywhere in the feeder, may be used to solve it. If several feeders are constrained, one flexibility from each constrained feeder may be used to solve them. If the MV/LV transformer is constrained, one flexibility, present anywhere in the downstream network may be used. If feeders and the transformer are constrained, feeder constraints are first solved. The additional flexibility to solve the transformer constraint from a flexibility already used is then evaluated.

Since many potential flexibilities exist in each feeder, the goal of the method is to find the best location of flexibility to solve a given set of constraints. Consequently, all feasible combinations of flexibilities across feeders are evaluated. The result of this method is hence a range of flexibility values. The heuristic rules and steps to be taken by the method outlined in the algorithm are presented below.

```
input network, prod, consumption
run load-flow() → output V, I, Stransfo
find feeders and transformer in constraint
if only feeders in constraint
```

```
 5 |   construct flexibility combinations
 6 |   for each combination
 7 |       evaluate flexibility_value(feeder)
 8 |   end
 9 | elseif only transformer in constraint
10 |   construct list of flexibilities
11 |   for each flexibility in list
12 |       evaluate flexibility_value(transformer)
13 |   end
14 | elseif feeders and transformer in constraint
15 |   construct flexibility combinations
16 |   construct list of flexibilities
17 |   for each combination
18 |       evaluate flexibility_value(feeder)
19 |       evaluate flexibility_value(transformer)
20 |     end
21 | end
22 | repeat 1 – 9 for all time periods
```

For feeder constraints, the algorithm evaluates all possible combinations of flexibility (constructed in Steps 5 and 15) across the constrained feeders. In the case of transformer constraints, a list of flexibilities is made (Steps 10 and 16).

The function `flexibility_value()`, in Steps 12, 18 and 19, uses a dichotomy-based search heuristic. It begins by setting the absolute lower and upper bounds for flexibility (0 and the maximum value). Then, it tests a small value for the flexibility and evaluates the impact on constraint resolution. If it is not solved, it updates the lower bound to the tested value, doubles the value of the flexibility, and continues testing until the constraint is solved. At all iterations where the constraint is not solved, it updates the lower bound. This lower bound therefore represents the highest value of the flexibility for which the constraint remains unsolved.

If a particular tested value solves the constraint, the upper bound is updated to this value. The upper bound is the lowest flexibility value for which the constraint is solved. The heuristic thus knows the bounds within which the lowest possible value of flexibility is located. It uses a binary search routine to fine-tune the lower and upper bounds. Once these two bounds converge to within a reasonable value of error (1 W for example), the value of the upper bound is the lowest possible value of flexibility.

Diffuse Flexibility Method

This method is also a heuristic search method. Here, constraints are solved using a set of flexibilities chosen according to the following rule. The flexibilities chosen to solve a constraint share the burden "fairly". The power modulation necessary from all these flexibilities is therefore a constant factor of the consumption in the node where these flexibilities are connected.

```
 1 | input network, prod, consumption
 2 | run load-flow() → output V, I, Stransfo
 3 | if constraints exist
 4 |     continue
 5 | else
 6 |     break
 7 | end
 8 | run group_constraints()
 9 | select first group of constraints
10 | construct flexibility set
11 | evaluate flexibility_value()
12 | apply flexibility values
13 | goto Step 2
```

If constraints are detected in a network, the algorithm first groups and classifies them using the function `group_constraints()`. The grouping of current constraints is done for consecutive constraints of the same type, in the same phase, and not separated by a branch. This is illustrated in Figure 1.

All voltage constraints in a feeder, irrespective of phase, are grouped together. We saw that flexibility activation in a phase created imbalance and neutral currents, changing voltages on other phases. Hence, we solve voltage constraints across phases in a combined manner.

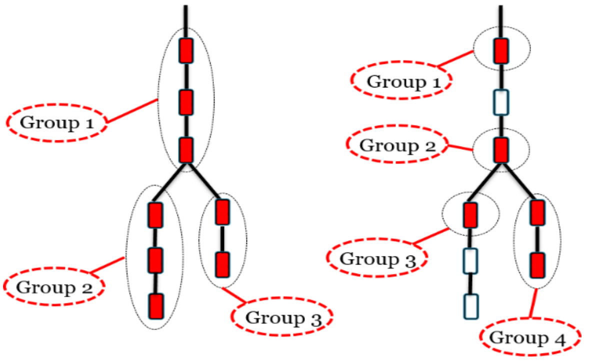

Figure 1 – Constraint Grouping – Diffuse Flexibility Method

The classification order for constraints is: current constraints, transformer constraints and then voltage constraints. If several constraints of the same type exist, they are arranged in the ascending order of customers affected by the constraints. If more than one constraint affects the same number of customers, they are then arranged in the descending order of constraint value.

The algorithm then selects the first group from the groups of constraints (Step 9). In Step 10, it identifies a set of flexibilities to solve the chosen group, based on the following rules. For current constraints, all the flexibilities on the same phase, downstream of the group are considered. For voltage constraints, all the flexibilities across phases in the same feeder as that of the constraints are considered. For a transformer constraint, all the flexibilities in the network are considered.

The `flexibility_value()` function used in Step 11 is very similar to the function used in the Exhaustive Placement method in that it uses a dichotomy-based search heuristic. The rules for this function, however, are different. For each flexibility to be used, a fictional contract power is first established. This corresponds to the sum of all contract powers of the loads on the same phase and node as the flexibility. A third of the contract powers of three-phase loads are considered.

Flexibility limits are set as follows. The flexibility can decrease the nodal load consumption in its phase down to 0. The downward flexibility available is thus the sum of all consumptions on the same phase and node as the flexibility. The flexibility can increase load consumption from the actual nodal consumption on the same phase, up to the sum of all corresponding contract powers. The upward flexibility is thus the difference between the sum of contract powers and the actual consumption.

The variable used by the dichotomy-based search is a percentage factor of the fictive contract power of the flexibility. This percentage value is the same for all flexibilities used to solve a constraint, and ensures that each considered flexibility participates “fairly”. Once the final percentage is found with the search, the corresponding flexibility values are applied (Step 12) to solve the group of constraints considered in Step 9. The algorithm then jumps to Step 2, and process continues onwards until there are no constraints left to be solved.

TESTS AND RESULTS

Tests on the 9 real-world LV networks were performed using Matlab® interfaced with OpenDSS. The mathematical optimisation was implemented using the *fmincon* toolbox. DisNetSimpl, a proprietary software developed at EDF R&D, and running on Matlab, was used for importing networks from Nice Smart Valley and for implementing the Diffuse Flexibility Method.

The 9 networks were tested over 1920 time periods in the year 2035 as described by the scenario (20 test days, 48 periods per day, with 2 PV scenarios PVMax and PVMin). Among them, 3 networks present constraints.

Table 1 – Constraints in the Tested Networks for the 20 Test Days

Network	**Constrained Time Periods (out of 960)**							
	Low Voltage		**High Voltage**		**Current**		**Stransfo**	
	No.	%	No.	%	No.	%	No.	%
5	135	7.1	-	-	-	-	-	-
8	100	5.2	-	-	-	-	-	-
9	89	4.6	-	-	-	-	-	-

The main observations to be made from these results are the following. The networks are robust and present few constraints for the simulations realised. Network 5 presents low voltage constraints 7.1% of the time over the 20 test days (1920 tested time-periods). The other two networks present fewer constraints, at 5.2% and 4.6% respectively. The networks present no high-voltage constraints, though many of them see reverse power flows.

The low voltage constraints also mostly occur in the evenings, correlated with high consumption. The number and nature of constraints does not change much between the PVMax and PVMin scenarios. This further reinforces the notion that the constraints are all related to high net consumption in these networks.

The flexibility evaluation methods were then tested on these networks. The results obtained for the PVMax scenario (maximum PV production) are illustrated in Figure 2 for Network 5, Figure 3 for Network 8, and Figure 4 for Network 9. In these figures, the daily volumes in kWh obtained with the three methods are illustrated. These results are briefly discussed afterwards.

The values obtained through the Optimal Reference method are presented in blue. The Exhaustive Placement method provides a range of flexibility values depending on their placement and the minimum value is retained in these figures and presented in orange. Finally, the values obtained from the Diffuse Flexibility method are presented in yellow.

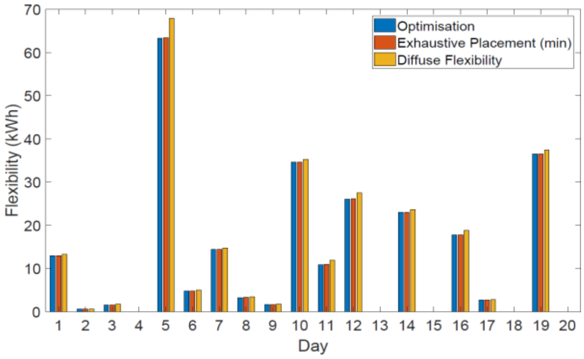

Figure 2 – Flexibility Volumes – Network 5 (PVMax)

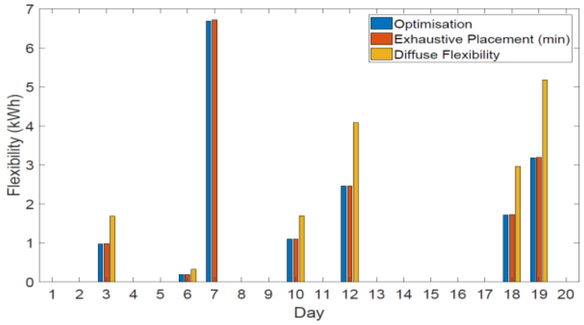

Figure 3 – Flexibility Volumes – Network 8 (PVMax)

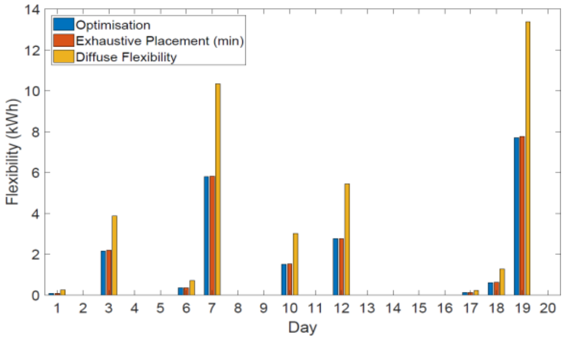

Figure 4 – Flexibility Volumes – Network 9 (PVMax)

The following inferences can be drawn from the results. For all networks, the Optimal Reference method performs the best in terms of minimising the flexibility volumes necessary. The minimum and maximum daily volumes (in kWh) obtained through this method for the 20 test days are shown in Table 2. The table also presents the maximum and minimum potential power necessary from flexibilities in the network for these test days.

Table 2 – Min. and Max. Power and Daily Flexibility Volumes for the 20 Test Days – Optimal Reference Method

Flexibility	**Network**		
	5	**8**	**9**
Min. Power (kW)	0.133	0.031	0.016
Max. Power (kW)	31.099	2.693	4.172
Min. Volume (kWh)	0.548	0.188	0.081
Max. Volume (kWh)	63.294	6.686	7.699

The Exhaustive Placement method has a very similar technical performance, with an average overestimation of only 0.91%. In addition, its execution times are much lower than the Optimal Reference Method. Since this method converges for all time periods with constraints, it can be said that for the given test networks, one flexibility per feeder could be sufficient to solve all the constraints that occur in the same feeder.

However, in some cases, the value of downward flexibility necessary is higher than the corresponding nodal consumption and may therefore be unrealistic. Figure 5 illustrates this for Network 9. The flexibility values to the left of the dotted diagonal line maybe unrealistic as they are higher than the corresponding nodal consumption. The Diffuse Flexibility method overestimates the flexibility by 43.4% on an average. Further, this method does not converge for one time period on Day 7 in Network 8. This is because the limit set for a flexibility that solves a voltage constraint occurring in its corresponding feeder is reached. While other flexibilities could have still solved the constraint, the concept of "fairness" would cease to be applied. The method does not, therefore, find a result in this case. A tweak to the method to lock flexibility that has already been used to its maximum limit would, however, be sufficient to overcome this issue.

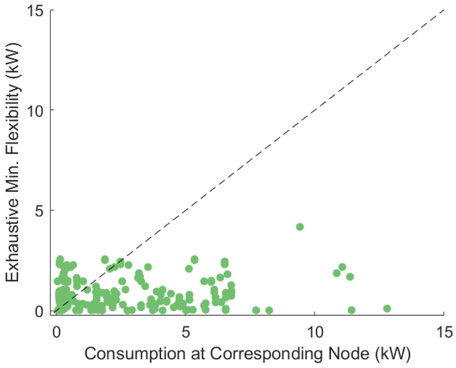

Figure 5 – Minimum Flexibility Value vs Nodal Consumption – Exhaustive Placement Method – Network 9

CONCLUSIONS AND FUTURE WORK

In the future, robustly designed LV networks may be confronted with new constraints related to evolutions in electricity production and consumption. If they become observable and controllable, flexibility may play a role in helping solve these constraints. However, the business case for flexibility use will probably have to be evaluated on a case by case basis in such a scenario. In general, if the conditions for flexibility use exist and are favourable, DSOs could integrate them in different work processes. In planning, this could potentially be used to avoid or defer investments. Consequently, in operational planning, this could result in the activation of relevant flexibilities to maintain LV networks, and probably even MV networks, under good operating conditions.

This article presented a study done for Nice Smart Valley project. It consisted in the development and testing of three different flexibility evaluation methods on 9 real-world LV networks in Nice and its surrounding areas. The study responded to an illustrative evaluation of the potentially necessary flexibility in a future context, foreseen for the year 2035 in the PACA region in France. The study tests the networks for a set of 20 test days on one instance of quasi-random PV generation and EV charging point placement. The results obtained were also presented and discussed.

The study shows that heuristic methods can perform relatively well, especially if the rules for these methods are well chosen, as these rules ultimately influence the quality of the results. Another conclusion is that one flexibility per feeder may be sufficient to solve the constraints observed in the networks and that the corresponding flexibility value is at least theoretically feasible in most cases. Many questions are still open regarding replicability and do need additional works but still, the study allowed to go several steps beyond regarding flexibility use optimization methods.

Some avenues for future work include the consideration of Monte-Carlo based methods for the generation of several instances of PV generation and EV charging point placement, and the inclusion of other evolutions in electricity end-use.

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