A reliability-based optimal number of PMUs for profitable fault location on MV feeders

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***Abstract*—This paper presents an economic assessment of a fault location method designed for medium voltage (MV) distribution grids leveraging distributed additional voltage measurements on some secondary substations. The aim is to provide a distribution system operator (DSO) with the optimal number of additional voltage measurement devices to make a fault location method (FLM) that has been developed in previous work as profitable as possible. Indeed, this optimal placement algorithm for this FLM provides a priority order for additional measurement location. However, the profitability of installing additional measurements derives from the gain in reliability that it achieves. This paper proposes an algorithm to optimally find the number and location of both remote-controlled switches (RCSs) and manual switches (MSs) of distribution networks based on reliability indices – with objective values fixed by the regulator. Then, the optimal number of additional measurements, which can be phasor measurement units (PMUs) for instance, is presented. The method has been tested on some realistic feeders reconstructed from Enedis's open database.**

Keywords— economic assessment, fault location, MV distribution grids, optimal switch and measurement placement, reliability

I. INTRODUCTION

Increasing the distribution system reliability is a constant objective of DSOs, firstly on MV grids. Indeed, customer satisfaction is highly correlated with the outage time and frequency. That is why reliability indices have been proposed and used in the literature to quantify these phenomena. First, the most commonly used index is the Expected Energy Not Supplied (Expected ENS, or EENS), which is the mean on a feeder of the product of the failure rate of each line with the power of the customers in an outage when the given line is faulty and with the time duration of the said outage (defined in [1]). This index depends on the power of the customers and as such emphasizes outages on the more powerful consumers (institutions, industries, etc…) with respect to smaller clients. Moreover, this indicator alone does not differentiate many short outages from longer but less frequent ones. That is why two other reliability indices have been proposed: the System Average Interruption Duration Index (SAIDI) and the System Average Frequency Interruption Index (SAIFI). SAIDI is the average duration of an outage for a client in $[min.client^{-1}.year^{-1}]$ while the SAIFI is the average number of outages faced by a client in $[outage.client^{-1}.year^{-1}]$.

Usually, MV grids are operated with a radial topology and are instrumented only at the busbar, where voltage and current are measured for each feeder with low sampling frequency (less than 10 kHz). When a fault is detected by the relay, the DSO operators receive information from the Fault Passage Indicators (FPIs) located on each of the remote-controlled switches (RCSs) distributed along the feeder. With these pieces of information, the DSO is able to reconfigure the network by isolating remotely the fault in a zone between two RCSs. Then, a maintenance team is sent to inspect the feeder looking for the fault position. Once found, they can open the manual switches (MSs) closest to the fault so that the outage is reduced to a smaller area. Finally, the system is repaired and then restored in nominal topology. With this procedure, it appears that there are two main ways to improve reliability (reduce SAIDI and SAIFI): 1) increase the number of switches (RCSs or MSs) so that the outage area at each stage of the system reparation is reduced or 2) deploying a fault location method (FLM) so that the time for line inspection is reduced.

In the literature, there are many proposed solutions for optimally placing RCSs and or MSs considering both costs and reliability in the objective function. In [2],[3], a Mixed-Integer Linear Programming (MILP) formulation is used to obtain the optimal placement for both RCSs and MSs on distribution grids. It shows that placing some RCSs and/or MSs can reduce the EENS by a factor of two with a reduction of the total cost (being the sum of the cost of switches and the cost of EENS) by almost the same factor. Thus, it is demonstrated that placing RCSs and MSs is economically profitable for DSOs. [4] takes into account uncertainties in load changes and system failure rate thanks to the point estimation method. Besides, [5] uses another placement method to minimize a total cost function depending on the cost of switches and on the cost of ENS. All the above-mentioned papers use the cost of ENS as part of the objective function to minimize. However, the definition of such cost is sensitive to a high number of parameters [6] since the estimation of the value of the lost load is a difficult task. This means that the objective function itself is difficult to define precisely when using the cost of ENS. This can be solved with the use of a Pareto front, as in [1], to accommodate the objective of minimizing SAIDI and the cost of switches. Moreover, [7] uses a Barnacles Mating Optimization algorithm to minimize a combination of SAIDI, SAIFI, and EENS instead of the cost of EENS.

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The economic profitability of deploying FLMs into distribution grids is rarely assessed (compared to the locating performance of the different methods). In [8] and [9], the installation of FPIs and the deployment of a FLM are compared in terms of reliability. It is shown that FLM can help further reduce SAIDI by around 5% more than when only FPIs are placed. However, this result is very sensitive to the accuracy of the fault location, which is generally low when dealing with compensated grounding on MV feeders. The results show that the fault should be located at a distance being in a range of $\pm 20\%$ of the estimated distance for a fault location algorithm to be profitable. However, the main limitation of this analysis is to consider a range of errors on the same branch in a radial feeder. Indeed, single-end impedance-based FLMs are confronted to the multiple estimation problem when applied on radial distribution feeders, meaning that there are several estimated fault positions potentially far from each other: this has not been considered in the literature. That is why this paper proposes to evaluate the profitability of the deployment of a FLM designed for MV radial distribution feeders which has been presented in [10] and further studied in [11]. This method has been shown to be able to locate any type of earth faults into a connected area the size of which depends on the number and location of additional voltage measurements placed at some secondary substations. An optimal placement algorithm has been presented and provides the DSO with a placement priority order, but the optimal number of additional measurements is yet to be given and depends on the gain in reliability.

This paper is structured as follows. Section II presents the optimal placement of RCSs and MSs algorithm and the computation of profitable number of additional measurements to deploy the FLM. In Section III, some simulation results obtained on 20 reconstructed realistic feeders are shown. Finally, Section IV concludes the paper.

II. Methodology

A. Reliability computation

In this paper, we consider only permanent faults. The Fault location, Isolation and Service Restoration (FLISR) process can be divided into 3 stages: 1) First, once the permanent fault is detected, the circuit breaker trips, and the DSO opens and/or closes some RCSs thanks to the information of the FPIs present at the RCSs' locations so that the outage area is as small as possible. During this stage, all clients on the feeder are experiencing an outage. The duration T_1 of this stage is usually between 1.5 min and 5 min in France [12]. 2) Once the outage is contained in the area between its two closest RCSs (named RCS area), the maintenance team is sent to find the fault location inside the RCS area. Once found, the team manually opens the MSs so that outage area is further reduced to the one between two RCSs or MSs the closest to the fault (named MS area). This stage takes usually between $T_2 = 30$ min and 60 min and depends on the length of the lines inside the RCS area. 3) In the last stage, the team clears the fault on site while only clients in the MS area are not supplied, then the system is restored in nominal conditions. This stage can take between $T_3 = 60$ min and 120 min. At the end of the stage 3, the supply will be restored for all customers. It should be said that the presented methodology can be applied to different countries in which the numerical values of T_1, T_2, T_3 are different. According to French fault statistics [13], 1.3 fault per kilometer of conductor has been observed by the main DSO, 3.6% of them being permanent ones. This means that the permanent fault rate is around $0.047\ fault.km^{-1}.year^{-1}$. In order to take into account the fact that faults are less likely to happen on overhead lines (OHL) than underground cables (UGC), we propose to use a differentiated fault rate as given by (1) [13]:

$$\begin{cases} \tau_f^{OHL} = 0.06\ fault.km^{-1}.year^{-1} \\ \tau_f^{UGC} = 0.04\ fault.km^{-1}.year^{-1} \end{cases} \quad (1)$$

In order to compute the reliability indices, we consider a permanent fault occurring on the line section k (being the line section upstream of node k) of length L_k on a grid. Then, the whole feeder is in outage during $T_1 = 5\ min$, after which only the clients in the area between the two closest RCSs are in outage during a time $T_2 = T_{2,0} + T_2' \times L_{RCS}^{tot}$ where $T_{2,0} = 30\ min$, $T_2' = 60/50\ min.km^{-1}$ (linked to the inspection speed of the team chosen to $50 km.h^{-1}$), and L_{RCS}^{tot} is the sum of the length of the lines inside the RCS area. Finally, only clients inside an area between the two closest RCSs or MSs are still not supplied during $T_3 = 90\ min$. An example is shown in Fig. 1 on the CIGRE MV benchmark network [14] (CIGRE network) with $k = 7$ i.e. a fault on line L_7 close to node 8. Then, SAIDI and SAIFI are computed for each line section according to (2), considering that there is at least a Tie switch in each area to restore the power. Since we do not dispose of the number of clients, the indices are computed with load power:

$$\begin{cases} SAIDI(k) = \tau_f(k) L_k \left[T_1 + \left(T_{2,0} + T_2' L_{RCS}^{tot} \right). \dfrac{P_{RCS}}{P^{tot}} + T_3 \dfrac{P_{MS}}{P^{tot}} \right] \\ SAIFI(k) = \tau_f(k) L_k . \dfrac{P_{RCS}}{P^{tot}} \end{cases} \quad (2)$$

With P_{RCS} being the sum of the power of the loads located inside the RCS area, P_{MS} being the sum of the power of the loads located inside the MS area, and P^{tot} the total power of the loads connected to the feeder. In this example, $L_{RCS}^{tot} = L_{11} + L_{10} + L_9 + L_7$, $P_{RCS} = P_7 + P_8 + P_9 + P_{10} + P_{11}$, and $P_{MS} = P_8 + P_7$. On the whole feeder, $SAIDI = \sum_k SAIDI(k)$ and $SAIFI = \sum_k SAIFI(k)$.

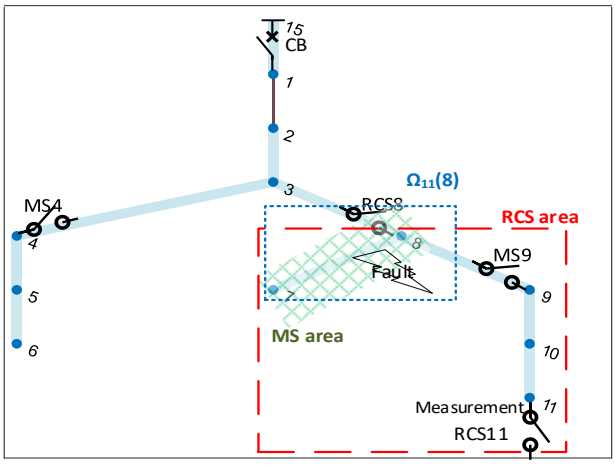

Fig. 1. CIGRE network with example of RCS area (red dashed lines), MS area (green barred area), and Fault location area with measurement at node 11 and fault at node 8 ($\Omega_{11}(8)$ in blue dotted lines)

B. Value of reliability

The French energy market regulator named CRE fixed objective values for both SAIDI and SAIFI for MV and LV clients in [15]. Considering that 5% of the clients of the

French DSOs are directly connected to MV grids and 95% to LV grids, we get objective values as follows (3):

$$\begin{cases} SAIDI_{obj} = 60.95\ min.client^{-1}.year^{-1} \\ SAIFI_{obj} = 1.34\ fault.year^{-1} \end{cases} \quad (3)$$

The regulator also established a financial incentive for DSOs to reach these objectives in the form of bonus or malus, creating a value of reliability, abbreviated as VoR in (4). Since this value is defined at the national level, the ratio P^{tot}/P^{Enedis} is needed to scale the incentive at the level of the considered feeder, with P^{Enedis} being the total power of the load at the national level. Using this incentive, we compute a Net Present Value (NPV), defined by (5) [15], to assess an investment (placing a RCS, a MS or a phasor measurement unit (PMU)) done only at $t = 0$.

$$VoR = \frac{P^{tot}}{P^{Enedis}}[6.375 \times 10^6.(-SAIDI + SAIDI_{obj}) + 4.8 \times 10^6.(-SAIFI + SAIFI_{obj})] \quad (4)$$

$$NPV = -CAPEX + \sum_{t=0}^{T-1}[VoR.(1+\alpha)^{-t}] \quad (5)$$

Where $CAPEX = C_{MS} \times nb_{MS} + C_{RCS} \times nb_{RCS}$ being the cost of installing switches (in this paper, the considered values are C_{RCS}=10k€ and C_{MS}=5k€), as discussed in the next parts. In this paper, $T = 10\ years$ is chosen as planning horizon and with the discount rate $\alpha = 5\%$ per year.

C. Reconstructed realistic French MV feeders

In appendix B of [16], 20 MV feeders from the same primary substation have been reconstructed from the open database of Enedis. For each reconstructed feeder, its topology with line section impedances and load data are given. However, the number and location of switches is not available on the database. That is why there is a need to place a realistic number of RCSs and MSs in realistic positions. The Fig. 2 presents the topology of the 19th reconstructed feeder with its main artery – defined as the path from the busbar to the most remote node on which a normally open RCS is placed to power some of the feeder from another one. This feeder is mostly a rural feeder of 186 nodes with a distance to the most remote node $d_{remote} = 29.57\ km$, with the sum of the length of the lines being $L^{tot} = 68.83\ km$, meaning that its rami-fication index is $ram = L^{tot}.d_{remote}^{-1} = 2.33$ and loaded with a total of $P^{tot} = 3.3\ MW$.

1) Placement of RCSs

According to French technical documentation [12], the RCSs are usually placed along the main artery of the feeder so that the different RCS areas have the same product $P_{RCS} \times L_{RCS}^{tot}$ (so that equality in outage time is ensured across all clients). Moreover, 2 RCSs are usually spaced by at least 2 nodes, so if the main artery is composed of A nodes, the number of RCSs should be inferior to $nb_{RCS}^{max} = ceil\left(\frac{A-6}{3}\right)$ with $ceil(x)$ being the smallest integer superior to x. To optimally place a given number of RCSs nb_{RCS} (which would be 5 in the example of Fig. 2) on the main artery of the feeder, we search the set of positions of the RCSs, $X_{RCS} \in [\![1, A]\!]^{nb_{RCS}}$, that minimizes the variance $\sigma^2$of the products $P_{RCS}(X_{RCS}) \times L_{RCS}^{tot}(X_{RCS})$ (6):

$$\hat{X}_{RCS} = \arg\min_{X_{RCS}} \sigma^2\left(P_{RCS}(X_{RCS}) \times L_{RCS}^{tot}(X_{RCS})\right) \quad (6)$$

This is a combinatorial problem that can be solved with an exhaustive grid search since the number of combinations remains small enough.

2) Placement of MSs

Following the placement of RCSs, the placement of MSs is done iteratively one by one in each RCS or MS area (in the one with the highest product $P_{RCS} \times L_{RCS}^{tot}$) in order to minimize the variance between the products $P_{MS} \times L_{MS}^{tot}$ of newly created MS areas. In this part, an exhaustive search of the best node for MS placement is employed since the number of nodes in each area remains small enough.

3) Number of RCSs and MSs

We search first for the optimal number of RCSs and MSs that need to be placed. This is obtained from extending the work of [17], [18] with the search for the optimal value for the number of RCS and MSs so that the NPV is maximized for the DSO (7). The optimization problem is solved under the hypothesis that the economic value of the nth RCS or MS is inferior to the one of the (n-1)th. Hence, we place at the first iteration $nb_{RCS} = 0$ RCS, then we place an increasing number of MSs until the NPV decreases (this is the best number of MSs for this number of RCSs with highest NPV). We repeat with one more RCS until the highest NPV obtained with nb_{RCS} is inferior to the one obtained with $nb_{RCS} - 1$. For instance, on the 19th feeder presented in Fig. 2, the optimal number of switches found by our algorithm is $\widehat{nb}_{RCS} = 8$ and $\widehat{nb}_{MS} = 5$.

$$\left(\widehat{nb}_{RCS}, \widehat{nb}_{MS}\right) = \arg\max_{nb_{RCS}, nb_{MS}} NPV \quad (7)$$

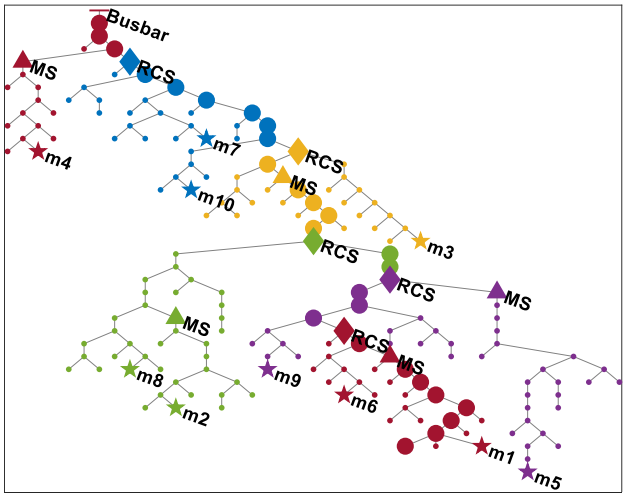

Fig. 2. Topology of the 19th reconstructed feeder with its main artery (bigger nodes), optimal placement of 5 RCSs (diamond nodes) and 5 MSs (triangle nodes) and with the top 10 measurement priority order for the FLM (star nodes labelled m1 to m10). Each RCS area is matched to one color.

D. Profitable number of additional measurements for fault location

The previous algorithm has been tested on 20 realistic feeders. On some of them (the 3 most highly ramified), the values of SAIDI and SAIFI are not compliant with the objectives. We propose the deployment of the FLM described in [10] and detailed in [11] to further reduce the value of SAIDI, and by such the operating costs of the DSO. This FLM needs the installation of additional voltage measurement on some secondary substations. It can locate

any type of earth fault inside an area composed of the nodes which are lateral to the projection node (which is the projection on the fault onto the closest path of nodes between an additional measurement and the busbar). For instance, in the example of Fig. 1, with an additional measurement on node 11 and a fault close to node 8 on L_7, the FLM will exhibit the node 8 and the solution area will be $\Omega_{11}(8) = \{8,7\}$ since node 7 is lateral to node 8 with respect to the path from node 11 to node 15.

Installing PMUs to perform fault location reduces the length of the lines that need to be inspected by the maintenance teams. Indeed, in the example of Fig. 1, the lines inside $\Omega_{11}(8)$ are L_7 (whole line), $L_8/2$, and $L_9/2$ (the closest halves of line to node 8). The lines that need to be inspected L_{scout}^{tot} are the lines inside the intersection of the fault location area and the RCS area of the fault: in the example $L_{scout}^{tot} = L_7 + \frac{L_9}{2}$, this will reduce SAIDI. In [10], [11], an optimal placement algorithm is proposed for the additional PMUs which provides the DSO with a priority placement order (shown on Fig. 2 with the labeled nodes m1 up to m10) that minimizes the expectancy of the length of the lines inside the solution area.

The deployment of such method comes at the cost of installing the voltage measurement, that can be PMUs for having the best locating performances and installing a phasor data concentrator (PDC) to store the measurements. To estimate the cost of installing such devices [19], we set the cost of each PMU at $C_{PMU} = 2450$ € (since we only need 3 voltage channels). With the installation of the first PMU comes the cost of the PDC, here $C_{PDC} = 8900$ €. With this, we can compute the capital expenditure (CAPEX) for the DSO: $CAPEX = nb_{PMU}.C_{PMU} + C_{PDC} + C_{MS} \times nb_{MS} + C_{RCS} \times nb_{rcs}$, with nb_{PMU} the number of PMUs. That is why we propose to iteratively place PMUs according to this priority placement order. Then, we search for the most profitable number of PMUs to place to deploy a FLM considering the theoretical performances (and solution areas) of the FLM (8):

$$\widehat{nb}_{PMU} = \arg \max_{nb_{PMU}} NPV \quad (8)$$

III. Simulation Results

A. Optimal switches placement

On the 19th feeder shown in Fig. 2, the main artery is composed of $A = 35\ nodes$ leading to a maximal value of 10 RCSs separated by 2 nodes. However, the most profitable number of RCSs to place is $\widehat{nb}_{RCS} = 8$ RCSs according to the results of the proposed algorithm which integrates the NPV criteria (5). Since the number of RCSs can be sometimes lower than the most profitable number, we compared the situation with 8 and 5 RCSs. That is why Fig. 2 shows the placement of 5 RCSs on the main artery of the feeder (for simpler visualization). After this first step (placing 5 RCSs), the variance of $P_{RCS} \times L_{RCS}^{tot}$ is still quite high: $\sigma^2\left(P_{RCS}(\hat{X}_{RCS}) \times L_{RCS}^{tot}(\hat{X}_{RCS})\right) = 4.32\ [MW.km]^2$ because of the green area which is quite long and loaded. In order to cluster the graph more uniformly, we would need to place RCSs on some lateral branches of the main artery. In the second step, we should place $\widehat{nb}_{MS} = 5$ MSs according to the optimization (7). However, the number of MSs is also sometimes lower than this optimal value. As such, Fig. 2 shows the placement of 5 MSs, with the first one being placed inside the green RCS area with the largest $P_{RCS} \times L_{RCS}^{tot}$, leading to a major decrease in the variance: $\sigma^2\left(P_{MS}(\hat{X}_{MS}) \times L_{MS}^{tot}(\hat{X}_{MS})\right) = 0.6\ [MW.km]^2$ with the 5 RCSs and 5 MSs.

B. Profitable number of additional measurements for fault location

On Fig. 3, we observe the impact of the deployment of the FLM on the value of SAIDI for 6 cases: with 5 RCSs or 8 RCSs and each with 3,5 or 7 MSs. This way, we can compare the profitability of the FLM with optimal and sub-optimal number of switches. Without additional measurement, with only 5 RCSs and 3 MSs (green curve on Fig. 3), the value of SAIDI was 65.7 min, which is higher than the objective value, which means the DSO would need to pay the market regulator some penalties. With the placement of a PMU on node m1 (Fig. 2), the FLM can be performed and can reduce the value of SAIDI by 7%, down to 61.3 min, which is around the objective value, as can be seen on Fig. 3. The placement of the second PMU increases the locating potential of the method so that SAIDI is further decreased to 59.8 min. The next PMUs have a lesser impact on SAIDI, which was to be expected, except for the 5th PMU (the placement of which leads to a greater reduction of SAIDI than the placement of the 4th one). Indeed, the optimal placement algorithm tries to minimize the expectancy of the length of the solution area without taking into account switches' placement. In this example, the purple area shown in Fig. 2 (in which m5 is located) is very large, so SAIDI would greatly be reduced from the placement of a PMU on node m5, which is located at the end of a long MS area.

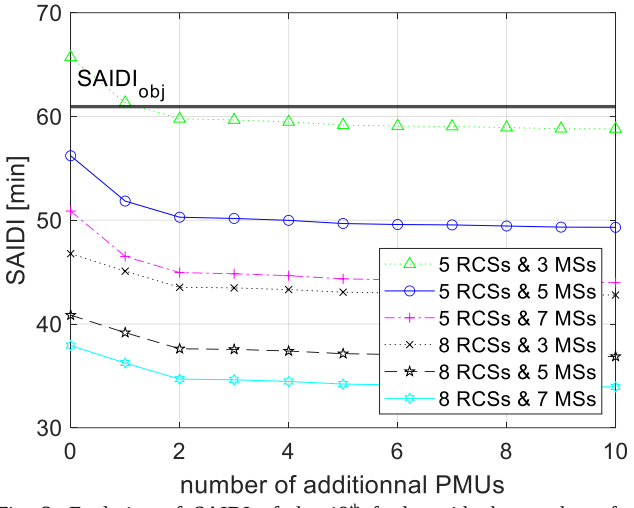

Fig. 3. Evolution of SAIDI of the 19th feeder with the number of additional PMUs and SAIDI objective value

The NPV as function of the number of placed PMUs is shown on Fig. 4. Yet again in the case of 5 RCSs and 3 MSs (green curve), without any PMU, the lack of feeder reliability can cost the DSO more than 83,700€ over the 10 years of planning horizon. The first PMU (with the PDC investment) can be very profitable due to the large increase of reliability that it leads to. Over the 10 years, the NPV is increased by more than 8,300€ with the use of 1 additional PMU to perform fault location. In this rural and highly ramified feeder, the second PMU is needed to obtain the best NPV as it increases by another 4,600€.

In the case of a high number of switches placed on the feeder (the cyan curve for instance), the first additional

measurement does not appear to be profitable since it decreases the SAIDI by only 1.6 min (5%), which means that its deployment would cost the DSO a loss of around 3,700€ in NPV over the considered time period. However, the placement of the 2 most priority measurements appears to be profitable for the DSO since it further reduces SAIDI and (in our model) does not increase the infrastructure cost (cost of PDC). In this example, the most profitable number of additional PMUs for fault location is the same, being 2 additional measurements, on all tested configurations without influence of the number of RCs and MSs.

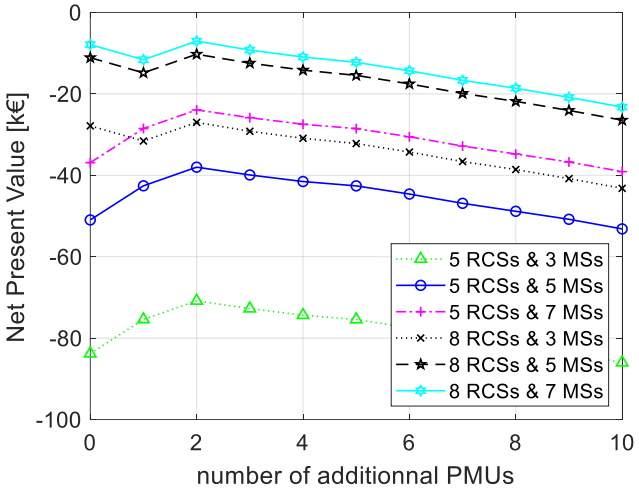

Fig. 4. Evolution of the NPV as a function of the number of additional PMUs placed on the 19th feeder

IV. Conclusion

This paper presents an economic assessment of a FLM designed for MV grids leveraging additional measurements. The optimal number of additional measurements is obtained by exploiting the gain in reliability that is induced by deploying a FLM on a reconstructed MV grid. The gain in reliability is translated into economic gain for the DSO with the penalties/bonus decided by the French market regulator. This way, the proposed methodology does not depend on the evaluation of the cost of EENS, which is very sensitive to a large number of parameters. The FLM appears to be tailored for the rural, long, and highly ramified feeders as it is on these feeders that the most profitable number of additional measurements is the highest. However, this paper proposes a simplified model for the inspecting time which is only function of the length of the lines. Future work should include more realistic paths of the maintenance teams. Besides, a thorough sensitivity analysis to different parameters such as the cost of PMUs and the success rate of the proposed fault location method ([10], [11]) should be carried out to better quantify the profitability of the location algorithm for a DSO. Moreover, as discussed in paragraph III.B, the optimal placement algorithm should consider position of switches to really obtain the best performances of the FLM. A new algorithm should be designed in that sense. For instance, on the straight-line urban feeder, the profitability of a single-end location method (such as a Takagi-based one [13]) should be evaluated. Finally, a reliability gain in SAIFI could be valorized if some non-permanent faults were located so that permanent faults could be avoided in the area.

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