Technical and Economic Assessment for Deployment of Distribution Automation Equipments – Enabling Self-Healing Strategies

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***Abstract* – This paper presents a methodology to evaluate technical and economic benefits achieved by deploying remotely operated switching devices (ROSDs) envisaging Self-Healing strategies. The network is firstly divided in several zones, having pre-existent ROSDs as boundaries and selecting the zone with higher energy not supplied (ENS). Thereafter, a failure event on the selected zone is evaluated with a cost/benefit analysis in the entire equipment life-cycle. Thereunto cost of energy not supplied, reduction on the electricity sales during the interruption, customer compensations and regulatory penalties/benefits associated with the quality of service are taken into account.**

This approach was applied to a real Portuguese distribution network for a case study. Reliability improvement as well as a payback period within equipment life cycle were achieved and presented.

***Index Terms* — Self-Healing, Distribution automation, Switching devices allocation, Reliability, Service restoration**

I. Introduction

Electrical power shortages are a major concern in distribution networks. From consumers or Distribution Network Operator (DNO) perspective, interruptions cause challenges with system stability and reliability. Economically speaking, service interruptions derive costumer's compensation costs, network repairing and/or providing alternatives for power supply, not even to mention on fear, inconvenience or loss of leisure activities extremely difficult to quantify due to their intangible nature [1]. Additionally, DNOs face penalties by not keeping quality of service (QoS) above fixed standards, defined by the regulator [2]. Besides, some studies, such as [3], tie service interruptions to Gross Domestic Product (GDP) reduction.

Hence, service restoration is required not only to reduce interruption costs but to improve QoS. The author of [4] supports a relation between customer satisfaction and service interruptions. In addition, the author defines service restoration main goal to perform load transferring from the outage area to other substation, supplying as many customers as possible in the shortest time. In addition, the author of [5] suggests that distribution network automation is the keystone to improve QoS and reduce maintenance costs.

With Smart Grids deployment and the change of paradigm in distribution networks operation, new capabilities emerge [6]. Self-Healing ability is a suitable example [7]. According to [8] taking advantage of real-time information from scattered sensors and automated controls, the self-healing can automatically avoid and mitigate service interruptions.

Though, to achieve automatic self-healing in a given distribution network, enhanced monitoring and widespread automation is required, along with appropriate allocation of Remotely Operated Switching Devices (ROSDs). These devices along with bidirectional communications schemes enable service restoration algorithms, such as [9], to perform self-healing strategies in service restoration. According to [10] using ROSDs to isolate a fault and reconfigure the network, provides service restoration within 20 seconds, in comparison to reclosers operation that takes several minutes, improving this way QoS as well as reducing interruption costs.

II. The Challenge

Empowering the distribution network with a service restoration scheme such as the self-healing entails major investments. For instance, costs with both communications schemes and network adaptation with new infrastructures or new hardware. Besides, distribution network operation may not be technically feasible with the new equipments, such as ROSDs. Meaning the addition of a new switching device to the network may compromise its operation once conductor current capacity and/or voltage limits are violated.

Thus, investment projects as these tackle two major concerns, economical and technical viability. This paper's main objective is to address these two concerns, developing a systematic tool to assess a cost/benefit analysis with ROSDs deployment in distribution networks. Evaluating therefore the achieved economic and technical benefits envisaging ROSDs operation within self-healing strategies.

III. Switching Devices Placement in Distribution Networks

The author of [11] describes an analytic methodology to find the "*optimal location and number of automation devices*". On his work, the author uses two objective functions, reduce

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interruption costs or maximize automation global benefits. Its field application, within the Italian distribution network, according to the author achieved global benefits ranging from 1,2 to 9 k€ per year.

Other approaches based on heuristics have been used to address the problem of finding strategic location to a load-shedding device [12, 13]. These algorithms have different objective functions; some of them optimize reliability indices [13, 14], whereas [12] minimizes outage, maintenance and investment costs using Simulated Annealing. In [15], the authors derive failure rates on trees-caused interruption events and evaluate customer interruption costs using fuzzy systems.

The author of [17] divides the distribution network into different zones having as boundaries protection devices, enabling performance analysis of individual zones within the feeder.

A. The Portuguese Distribution Network Operator Vision

According to [18], the Portuguese DNO uses for objective function the maximization of ENS reduction achieved with a new recloser. Therefore, the annual ENS is evaluated before and after the new switching device and maximized its reduction. In [19] the same procedure is referenced.

Economical analysis is also centered in ENS reduction. Both authors describe the cost/benefit analysis with a new recloser, taking into account reductions on interruptions times and hence costs reduction. The analysis is performed within the equipment's life cycle and uses a discount rate of 10% in order to determine the net present value.

Besides the authors' conformity on the methodology to evaluate reclosers' position, the author of [18] differentiates the method to deploy reclosers from ROSDs. According to the author, allocation of ROSD in the network follows an empirical evaluation of possible locations in longer overhead lines or near critical loads.

IV. Developed Methodology

Some initial assumptions were taken on the methodology. It was assumed that every fault results on a three-phase interruption. Even a single-phase fault was assumed to result in a three-phase interruption. Another consideration was the absence of multiple faults in the network. Meaning only one zone in the network is interrupted simultaneously. One more supposition was the consideration of all normally open points (NOPs) to be remotely operated, i.e. with a ROSD already serving as a switching device.

The presented method starts by acquiring the network parameters, step (1) in Fig. 1. performed by retracting information on lines length and type (overhead or cable), loads, electrical parameters and installed ROSDs.

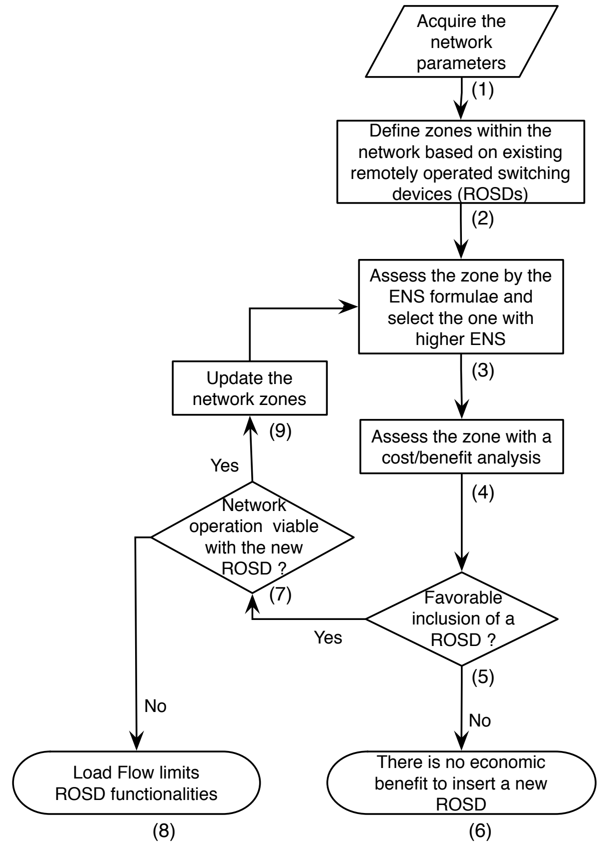

Fig. 1. Methodology flowchart

Step (2) uses the information of any existent ROSD in the network, which enables dividing the network into zones having the preexistent ROSD as boundaries. In case no ROSDs are found in the network, a zone is defined between the primary substation and the NOP at the end of the feeder. Fig. 2 shows an example of a possible MV network divided into several zones, having the preexistent ROSDs as boundaries separating each zone.

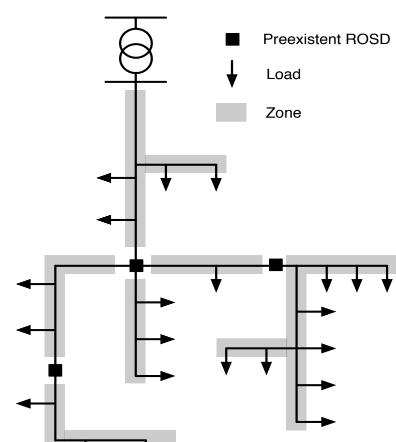

Fig. 2. Example of MV network with several zones

ENS is used to compare each zone in step (3). Therefore the zones are compared by their reliability performance. The one with higher ENS, thus low reliability, should be selected to perform the economical analysis with the new ROSD.

Further details on this step are given in section A.

Step (4) is used to assess the inclusion of a new ROSD in the selected zone. Performed by dividing the zone into two separate sections, regarding total load. Thus, including 1 ROSD results in dividing 50% of load to each side, 2 ROSD results in 33% of load and consecutively. Further details on this step are given in section B.

In step (5) the economical viability is evaluated performing a cost/benefit analysis within equipment's life-cycle. In step (7), the feasibility of distribution network operation with the new equipment is evaluated using a Load Flow. Further details on this step are given in section C.

Consequently, the network operation is either possible with the new ROSD, step (9), or having its functionalities limited by the network operation, step (8). With no voltage or current limits violated installing the new ROSD, the network zones should be updated in step (9) including the new ROSD.

A. Technical Analysis

The application of regulator penalties is associated with the annual value of ENS being below a reference value. Besides, ENS is easily converted into economical costs using the Cost of Energy Not Supplied (CENS). Furthermore, QoS in distribution networks is directly related to ENS. As a result, evaluation of each zone in step (3) is achieved by calculating the ENS independently.

$$ENS = \lambda \cdot L \cdot r \cdot P \cdot l_f \text{ [MVA.h]}, \quad (1)$$

where λ is the failure rate per kilometer in [fl/km], L the line length in [km], r the interruption time in [h], P total load in [MW] and l_f the load factor.

B. Economical Analysis

Planning investments are usually made foreseeing several years of network operation. Hence, the economical analysis is made foreseeing the ROSDs operation in their entire life-cycle, taking into account load growth rates and tariffs growth rate.

In the same way [12] uses the CENS to evaluate the economical cost of interruptions to costumers, the developed method also takes into account the CENS. Besides, using ENS to assess zones reliability, a linkage is made between economic and technical benefits. Equation (2) presents the calculation of CENS.

$$CENS = TIEPI \cdot P \cdot l_f \cdot V_{ENS} \cdot i_c \text{ [€]}, \quad (2)$$

where TIEPI is the interruption equivalent time for the installed power in [h], P is the installed power [MW], l_f the load factor, V_{ENS} is the ENS value in [€/kW.h] and i_C is the load growth rate.

During the fault, utilities have their profits reduced, since there are no electricity sales to the affected customers. Hence utilities are also affected with loss of revenue (LR) during service interruptions.

$$LR = \sum_{i=1}^{x} TIEPI \cdot P_i \cdot l_f \cdot t_i \cdot i_t \text{ [€]}, \quad (3)$$

where TIEPI is the interruption equivalent time for the installed power in [h], P_i is the contracted power for customer i in [kVA], l_f is the load factor, t_i is the tariff value for customer i and i_t is tariff growth rate.

Violating the interruptions frequency and interruptions total duration limit, each year, results in penalties to the DNO. In the Portuguese regulatory framework these penalties are calculated according to (4) and (5), respectively for interruptions frequency and interruptions total duration.

$$IF = (NI - NI_{REF}) \cdot V_{IF} \text{ [€]}, \quad (4)$$

where NI is the number of interruptions, NI_{REF} is the reference number of interruptions defined by the regulator and V_{IF} is the unitary value of compensation for exceeding the number of interruptions limit, in [€].

$$ID = (DI - DI_{REF}) \cdot P \cdot V_{ID} \text{ [€]}, \quad (5)$$

where DI is the total interruptions duration in [h], DI_{REF} is the reference for total interruptions duration defined by the regulator in [h], P is the contracted power in [kW] and V_{ID} is the unitary value of compensation for exceeding the total duration of interruptions limit, in [€/kWh].

Hence, penalties total cost is given by (6).

$$PC = IF + ID \text{ [€]}, \quad (6)$$

Likewise the regulation of interruptions frequency and duration and consequent application of penalties to the DNO, the annual value of ENS suffers a similar mechanism of regulation. In short, each year the regulator declares a reference value for the ENS and if the annual ENS surpasses this reference value, the DNO incurs in penalties, in the same way if the annual ENS stays below this reference value a subsidy is given to the DNO. Fig. 3 illustrates the way this regulation mechanism works in the Portuguese situation.

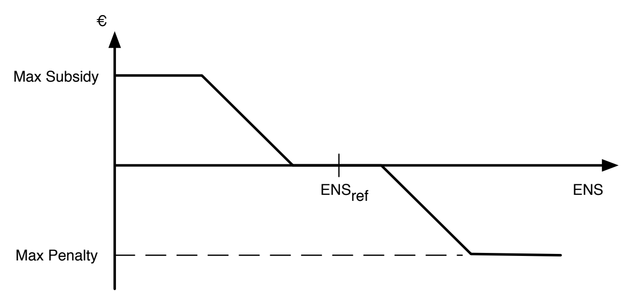

Fig. 3. Mechanism to incite quality of service improvement.

Equations (7) and (8) show the formulation when the ENS is below the reference value (subsidy situation) and ENS is above the reference value (penalty situation) respectively.

$$QSR = Min(QSR_{\max}; (ENS_{ref} \cdot i_{ENS} - \Delta V - ENS) \cdot V_{ENS}) \text{ [€]}, \quad (7)$$

where QSR_{max} is the maximum value for the subsidy in [€], ENS_{ref} is the reference value of ENS stated by the regulator in [kW.h], i_{ENS} is the ENS_{ref} reduction rate, ΔV is a tolerance value in [kW.h], ENS is the annual value of ENS in [kW.h] and V_{ENS} is the value of ENS in [€/kW.h].

$$QSR = Max(QSR_{min}; (ENS_{ref} \cdot i_{ENS} + \Delta V - ENS) \cdot V_{ENS})\ [€], \quad (8)$$

where QSR_{min} is the maximum value for the penalty in [€]. Since the regulator estimates the reference value of ENS (ENS_{ref}) according to previous records from 2 years time, adding the tolerance value (ΔV) reduces the probability for the DNO to incur in situations of penalty/subsidy due to random events, i.e. natural causes or significant reduction in consumption. Therefore, a situation where the DNO did not took any action to improve the network but even though having, in the present year, the ENS reduced by a small amount will not provide the DNO a subsidy.

Placing a new ROSD in the selected zone will create a separation into two new zones. Since load is not evenly distributed in the network, dividing equally 50% of load to each new zone is usually impracticable. Therefore the economical analysis should consider an interruption in the zone with higher amount of load, resulting this way in higher ENS.

Each of these economical components should be compared to the initial scenario, with no ROSD. Thus the result of equations (2), (3), (6) and (7) or (8) with a new ROSD has to be compared to the previous result of no ROSD installed, i.e. the initial costs/penalties reduced from the final costs/penalties. Resulting this way in costs reduction, since there are no direct profits in installing a new ROSD.

For the investment scenario two types of equipment's were used, remote operated switching device with reclosing capability for overhead lines and a Distribution Transformer Controller (DTC) [10] for underground networks. Within the total price it should be included the maintenance cost, installation and acquisition cost. Maintenance costs for the equipment's life cycle will be calculated according to the acquisition cost, used in [19] analysis as 2% of the initial acquisition cost. Enabling its calculation as a single cost, instead of several yearly or monthly amounts.

$$I = C_A + C_I + 0{,}02 \cdot C_A\ [€], \quad (9)$$

where C_A is the acquisition cost, C_I is the installation cost and $0{,}02.C_A$ are the maintenance costs. Thereby, using (9), the investment cost is obtained as a single amount for the entire equipment's life cycle.

C. Load Flow validation

Even with economic viability from installing a new ROSD in the distribution network, its operation has to be validated regarding voltage and current limits. Since service restoration within self-healing strategies foresees load transfers to other substation, conductor's current has to be kept under their capacity. In the same way, voltage drop on every load point needs to be over specified limits.

In order to guarantee ROSD full operation within self-healing strategies in coordination with feeder normally open points (NOPs), the network needs to be submitted to a load flow calculation and validation. Doing a load transfer, in the worst-case scenario of energy demand, conductor's current capacity (thermal limit) and voltage drop in load points has to be within their specific limits.

V. Case Study

Applying the developed methodology to a case study has essentially as main objective to confirm it within a real scenario. Therefore, it was employed on a real MV distribution network.

In particular, a section of the Portuguese south region distribution network was employed. Connecting 3 primary distribution substations (60 kV / 15 kV), with installed power of 10, 20 and 63 MVA, 2 wind farms with 50 and 55 MVA, 11 NOPs and secondary distribution substations with total installed power of 80,94 MW. Fig. 4 show the network employed.

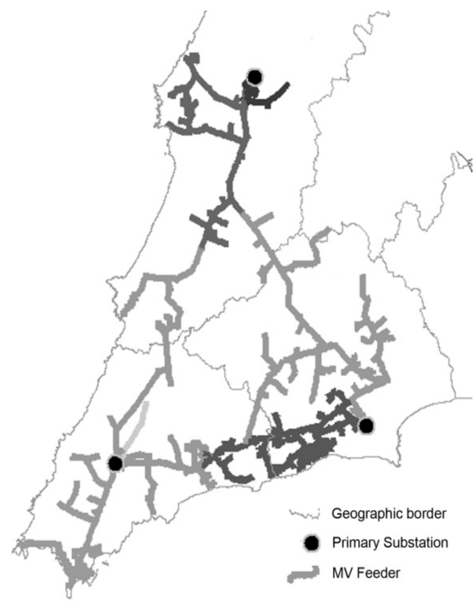

Fig. 4. Distribution network used for the case study.

The network is mainly composed of overhead feeders, with just 2 underground feeders. Apart from the numerous reclosers spread through the overhead feeders, there is no ROSD on the entire network. Therefore, zones division envisioned at Fig. 1, step (2), results in defining each zone starting at the substation and ending at the feeder NOP. Hence, the number of total zones in this case study equals the number of feeders, i.e. 8 zones/feeders.

A. Zones Evaluation upon ENS calculation

With the network divided in zones and assuming the occurrence of a fault in each zone, using equation (1) to assess ENS, the results were:

TABLE I
ENS results for all zones

Zone	Length [m]	Load [MW]	ENS [MW.h]
A	32 282	13,41	31,6
B	27 830	11,95	24,3
C	19 075	13,91	19,4
D	8 173	16,84	10,0
E	8 350	16,19	9,9
F	9 383	7,10	4,9
G	1 191	1,55	0,1
H	8 377	0	0,0

Failure rate and average interruption time used for the ENS calculation came from the DNO's 2009 quality of service report for the Portuguese south region:

- $\lambda = 0{,}0973$ [failures/km];
- r = 2,5 [h].

Since it was impossible to obtain data regarding the exact number of customers per secondary distribution substation, a 30% load factor calculated from the average peak demand in all network MV/LV substations was used in the calculation.

Zone H relates to an overhead line solely to connect one of the wind farms, having no loads, this way its ENS is as presented 0 [MW.h].

Following step (3) from Fig. 1 the zone with higher ENS should be selected. Therefore, from TABLE I, zone A is the one with higher ENS and its location is presented in Fig. 5.

Fig. 5. Selected zone with the higher ENS value.

The feeder has 32 282 [m] of total length, 9,37 [MW] in distribution MV/LV substations and 4,04 [MW] privately owned, a wind farm with 55 [MVA] of installed power and 3 NOPs.

B. Economical Assessment within Equipment's Life Cycle

The economical analysis used 4 different scenarios of investment: 1, 2, 3 or 4 ROSD. Hence, installing a ROSD in the selected zone causes its division into new zones. For instance in the scenario of 1 ROSD would split the zone in 2, as for the scenario of 4 ROSDs it would split the zone into 5 new zones, regarding total load.

Since loads are not evenly distributed, the zone division for the 4 scenarios resulted in:

- 1 ROSD – 55% and 45% of load to each side;
- 2 ROSDs – 36%, 26% and 38% of load to each side;
- 3 ROSDs – 36%, 26%, 16% and 22% of load to each side;
- 4 ROSDs – 18%, 18%, 26%, 16% and 22% of load to each side.

Therefore the costs reduction should be assessed using the worst-case scenario, i.e. for the higher percent of affected load with an interruption (55%, 38%, 36% and 26% in the 4 investment scenarios).

As stated in section IV. B. equipments have a 20 year's life cycle, under regular maintenance. Then economical analysis should also be assessed for a 20-year period. Though, in order to simplify results presentation, only the first year results will be presented thoroughly.

1) Cost of Energy Not Supplied

CENS calculation is given by equation (2), presented in section IV. B. Results for all the investment scenarios are shown in TABLE II, only for the first year of analysis.

TABLE II

CENS for all investment scenarios, for the 1st year.

	0 ROSD	1 ROSD	2 ROSD	3 ROSD	4 ROSD
CENS [€]	12 188	6 749	4 613	4 357	3 127

CENS calculation with: a TIEPI of 121 min/year from the DNO's 2009 quality of service report for the Portuguese south region distribution network, the unitary cost of ENS (V_{ENS}) of 1,5 €/kWh defined by the Portuguese regulator and a 3,1% annual demand growth rate to calculate CENS for the remaining 19 years.

Note that CENS reports to an interruption cost, therefore the profit is calculated subtracting the final CENS to the original value, i.e. with a 3 ROSDs scenario profit is 12188 € minus 4357 €, resulting in 7831 € of benefit.

2) Loss of Revenue

Loss of electricity revenue during the interruption is given by equation (3), presented in section IV. B. Results for all the investment scenarios are shown in TABLE III, only for the first year of analysis.

TABLE III

Loss of Revenue for all investment scenarios, for the 1st year.

	0 ROSD	1 ROSD	2 ROSD	3 ROSD	4 ROSD
LR [€]	886	477	424	306	134

LR calculation with: customers average contracted power of 6,9 kVA and 250 kVA for LV and MV costumers, tariffs prices for LV (0,1326 €/kWh) and MV (0,0876 €/kWh) customers defined by the regulator and a 2,5% annual tariffs growth rate to calculate LR for the remaining 19 years.

Note that LR reports to an interruption cost, therefore the profit is calculated subtracting the final LR to the original value, i.e. with a 2 ROSDs scenario the profit is 886 € minus 424 €, resulting in 462 € of benefit.

3) Costumers Compensations

Costumers' compensations are given by equations (4) and (5), and their sum by (6).

The number of interruptions and their total duration, referring to 2009, was 3 faults/year and 121 min/year. Since these quantities do not exceed the limits of 16 faults/year and 480 min/year, there were no costumers' compensations. Resulting in 0 € for all investment scenarios, even for the original scenario of 0 ROSD.

4) Incentive to Improve Quality of Service

Mechanism to incite quality of service improvement is given by equation (7) in case annual ENS is below the reference value or by equation (8) if annual ENS is above the reference value. Results for all investment scenarios are shown in TABLE IV, only for the first year of analysis.

TABLE IV
Incentive to improve QoS for all investment scenarios, for the 1st year.

	0 ROSD	1 ROSD	2 ROSD	3 ROSD	4 ROSD
QSR [€]	-4 214	-5 613	-5 942	-5 975	-6 100

QSR calculation with: maximum value of subsidy/penalty of 23 047 €, reference value of ENS (ENS_{ref}) of 0,0134 % of the total energy supplied within the feeder, ENS_{ref} reduction rate of 5,8%, ΔV of 12% of ENS_{ref} and V_{ENS} of 1,5 €/kWh.

Note that QSR values are all negative, meaning a subsidy was applied. Since a cost notation is used in all economical analysis, and with the QSR calculation results a subsidy for the DNO, the negative sign is used. Nevertheless the profit of having a new ROSD is given by the same way as the previous examples, i.e. with a 4 ROSDs scenario the profit is -4 214 € minus -6 100 €, resulting in 1 886 € of benefit.

5) Costs of Investment

As the selected zone is entirely composed by overhead lines, the DTC solution is not suitable. Therefore, all ROSDs are reclosers with the necessary equipment for remote operations. According to a supplier, a ROSD single unity costs 20 096 €, given by equation (9) in section IV. B. The total cost for each investment scenario is thus given by single unity cost times number of units, for instance for 2 ROSDs results in 2 time 20 096 €, totaling 40 192 €.

6) Overall Results

Since the economical analysis should be formulated for all equipment's life-cycle (20 years in this study), a discount rate should be used and consequently the net present value (NPV).

Hence, a discount rate of 10% was employed to calculate the NPV for the 20 years period. This way, a payback period could also be determined. In Fig. 8 both payback period and NPV are presented for all investment scenarios.

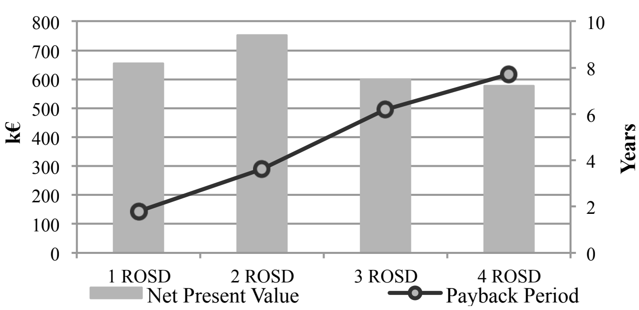

Fig. 6. Net Present Value and Payback period for all investment scenarios.

C. Load Flow Results

The Load Flow calculation was achieved using a SCADA/DMS software with a specific tool for Load Flow analysis. Namely the ScateX+ provided by Efacec, also used by the Portuguese DNO.

In order to evaluate any technical violations with the inclusion of a new ROSD, the following scenario was applied:

- No power injection from the wind farm within the zone;
- NOP closure and consequent ROSD opening.

It was selected the ROSD which on its opening, results in the major load transfer.

The 4 ROSDs scenario was firstly evaluated, closing the NOP at the end of the feeder and simulating a fault on the beginning of the feeder resulting on the first ROSD opening. Meaning, approximately 4/5 of total load were transferred to the other substation. Fig. 7 shows the feeder schematic after closing the NOP and opening the opposite ROSD, at the beginning of the feeder (see Fig. 5 for comparison).

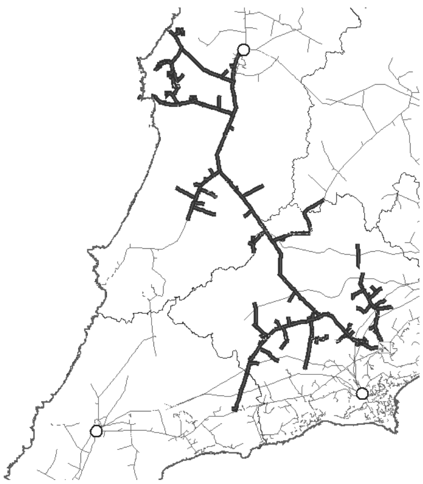

Fig. 7. Evaluated feeder after load transfer between substation (NOP closure and ROSD opening).

VI. Results Analysis

With the full life-cycle results, each economical component contribution was evaluated in the overall amount. Analyzing the average percent for each economical component within the 4 investment scenarios a predominant contribution was noticed.

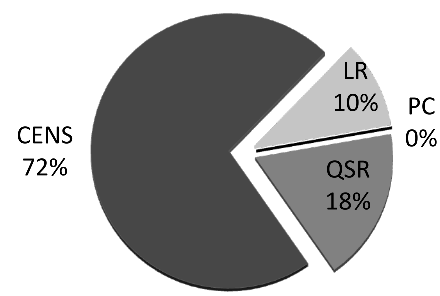

Fig. 8. Contribution of each economical component in the overall amount.

CENS plays a major role in the economical analysis. The reason behind that relies on the greater value of V_{ENS}, the unitary cost of ENS equal to 1,5 €/kWh. Meaning, it is more than 10 times greater than LV tariff (0,1326 €/kWh) and 17 times greater than MV tariffs (0,0876 €/kWh). On the other hand, since the mechanism to incite QoS improvement is already positive, adding ROSDs to the zone bring small benefits compared to CENS reduction.

Since TIEPI is the used time for modeling average total interruption duration in a year, and being used for all the economical components calculation, its impact should be considered. Therefore it was determined its influence in the payback period, ranging its value from -50% to +50% (61 to 182 min/year). The results are shown in Fig. 9. Note that, for the 3rd and 4th scenario, a reduction in TIEPI to 50% implies that the payback period is no longer within the 20 years life cycle.

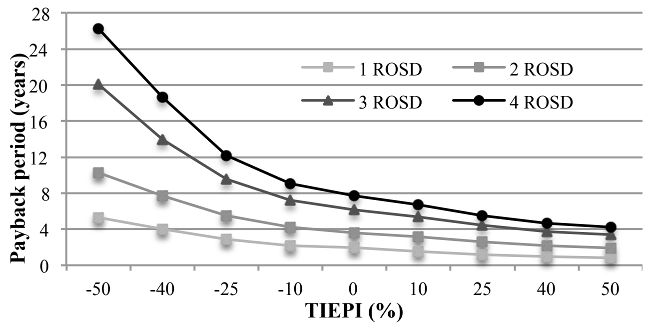

Fig. 9. TIEPI's influence in payback period.

Technical benefits were similarly evaluated with the installation of new ROSDs. As described in section V. B. the zone division with a new ROSD is hardly even, for instance with 1 ROSD resulted in a 45 – 55% division. This way, the worst-case scenario would be a fault on the 55% side, interrupting the most load.

Presented in Fig. 10, ENS value reduces with the number of ROSDs deployed. This was a consequence of reducing the zone in smaller sections each time a new ROSD was installed. Note that for 3 and 4 ROSDs the best scenarios have the same value of ENS, resulting from the same load division of 16%.

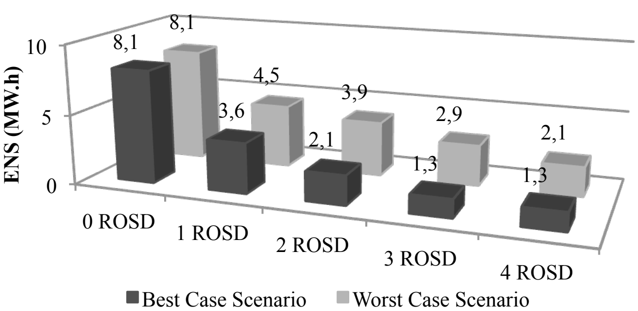

Fig. 10. ENS reduction for 1, 2, 3 or 4 ROSDs.

A similar improvement was achieved on the number of affected costumers with a fault, Fig. 11. Still, since zones have different number of costumers, besides ENS equals 1,3 [MW.h] with 3 or 4 ROSD (for the best scenario), the number of customers affected suffer a slight reduction.

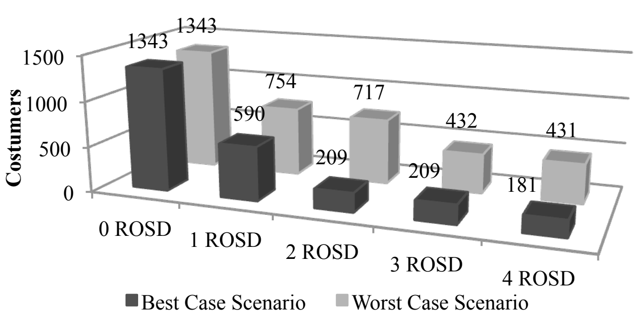

Fig. 11. Number of affected customers for 1, 2, 3 or 4 ROSDs.

VII. Final Remarks

Implementing Self-Healing strategies results in reducing the circuit breakers reclosing operations. This comes with the dispersion of sensors through the network, indicating the fault location. As outcome, circuit breaker detrition is reduced since reclosing operations in the presence of short circuit are reduced. This way, strategic deployment of ROSDs in the network is essential to improve quality of service.

A. Conclusions

Analysis results show a significant QoS improvement is feasible with ROSDs installation. According to Fig. 10 and Fig. 11, the number of affected costumers as well as the ENS suffers a reduction. In the given example, adopting different self-healing strategies (with 1, 2, 3 or 4 ROSDs) reduces the number of customers/loads and consequently the amount of energy interrupted when a fault occurs. Therefore, if fewer loads are interrupted during a fault, for the same time interval, ENS suffers a reduction (improvement) as more ROSDs are added, eventually reaching a saturation level.

Other major conclusion is the CENS major role in the economic analysis. Due to its value of 1,5 [€/kW.h], ten times greater than the LV tariff, and consequently its major influence in the payback period may compromise the viability of the economic analysis. Still, relative to the economical analysis, a major influence in the payback period occurs with the TIEPI variation. As Fig. 9 shows, a reduction of 50% in TIEPI means that the payback period, for this case study, is above 20 years, i.e. over the equipment life cycle.

The load flow validation revealed itself essential in order to confirm full operation of the new ROSD in the network. This step not only confirms the economical results achieved with the case study, meaning that in the presence of a fault, all functionalities of the new installed ROSD are available within Self-Healing strategies. On the contrary, ignoring this step of validating all functionalities of the new ROSD in the network could result in exceeding lines current flow capacities and/or voltage drop limits violation. Resulting, this way in the infeasibility to use that new ROSD to proceed to a service restoration within a Self-Healing strategy.

Having a generic tool, such as this one, enables a methodical analysis to be applied either to overhead or underground lines, as well as radial, open or closed meshed networks. Likewise the opportunity to adapt TIEPI values, failure rates, CENS and LV and MV tariffs to different scenarios of analysis allow a network analysis in different geographic regions.

Summing up, all the main conclusions can be grouped as:

- Significant quality of service improvement with ROSD deployment;
- Cost reduction is also achieved using ROSD for service restoration envisaging Self-Healing strategies;
- The economic viability of such project has been proved in the case study, having the payback period within the end of the ROSDs life cycle.

B. Major Contributions

Since the deployment of ROSDs envisages service restoration under Self-Healing strategies, the time required to isolate a fault and restore the service to customers is significantly less than using reclosers.

Using this systematic tool to assess strategic positions to deploy a new ROSD, the number of possible affected customers is known integrating the presented results such as the exact position of the ROSD installation. Consequently, knowing the number of affected customers and their installed power allows the calculation of the ENS with a fault.

Besides the costumers' costs, usually taken into account by other authors, this work includes as well the DNO associated costs. Specifically bringing into the calculation reduced revenue from electricity sales during a service interruption and the regulatory penalties associated with low quality of service provided to costumers. In order to assess regulatory penalties to the DNO, customers division is achieved by their voltage level. This way costumers connected to the MV level were given a higher significance compared to LV costumers.

C. Methodology Limitations

A limitation with the methodology was found during the case study. The loads quantity within a zone is not taken into account in the ENS formulae, and consequently not evaluated to select a strategic location for the ROSD. A given example is having two zones, with same length, failure rate, average interruption time and total amount of load but different number of loads (MV/LV substations). Resulting in equal values of ENS and therefore both should be selected for a ROSD installation. Though the zone with higher number of loads should be preferred resulting in a service restoration to a higher number of costumers. This situation is not differentiated in this methodology.

Planning results achieved with the analysis may be compromised with the site's geography, i.e. mounting a ROSD in a specific pole may not be easily accessible as mounting it in a neighborhood pole. Meaning, field teams easier do installation and maintenance operations on the ROSD. An answer may be found integrating this methodology into a GIS (Geographic Information System) and find a compromise to the obtained results.

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IX. Biographies

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