OPTIMAL RECLOSER DEPLOYMENT TO LEVERAGE SELF-HEALING: A TECHNO-ECONOMIC ROBUSTNESS ASSESSMENT

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ABSTRACT

This work presents a techno-economic robustness assessment over coordinated protection schemes using reclosers to leverage Self-Healing in distribution networks. A methodology to assess the optimal deployment of reclosers in overhead distribution networks is used to define the number and the strategic location of reclosers, in order to achieve the maximization of the reliability improvement and the investment cost effectiveness. The methodology comprises a technical assessment over the service restoration feasibility through Fault Detection, Isolation and Restoration (FDIR), and an economic assessment through a Cost-Benefit Analysis (CBA) over the equipment's life cycle. A real Portuguese distribution network is used to perform a case study comprising two scenarios of operation under contingency, a base case scenario and an additional scenario considering the presence of Renewable Energy Sources (RES) – Wind Power Plants (WPPs). The advanced sensitivity analysis focuses the evaluation of the optimal solution robustness to key parameters – technical and economic – such as the value of Energy Not Supplied (ENS), the load growth rate and the value of the wind curtailment.

INTRODUCTION

The investment in electric power systems reliability and planning is essential to ensure the continuous improvement of the Quality of Service (QoS) in the electric energy supply. The distribution system makes the greatest individual contribution to the unavailability of supply to customers, mainly due to unplanned service interruptions at the Low Voltage (LV) and Medium Voltage (MV) networks [1]. Power shortages are a great concern for the Distribution System Operators (DSOs), due to their significant impact in the QoS for which they are technically and economically responsible.

In Portugal, regarding electric energy supply, the technical QoS is related with the analysis of the continuity of service, which is evaluated by the Energy Not Supplied (ENS) and the number and duration of long and momentary interruptions.

Unlike most of the LV networks, the MV networks are typically operated on open mesh topology, allowing Self-Healing implementation to improve reliability. The goal is to supply the maximum load in the feeder affected by a fault during the outage period thus reducing the restoration time to minimum. This must be accomplished with the fewer number of switching manoeuvres possible, while preserving the network's operation within the technical limits [2].

Self-Healing may be based on different implementation strategies, using several distribution automation solutions for network remote operation in real time, through network high-speed communication empowering, hardware and software outfitting.

Concerning systems supervision and control, centralized, semi-decentralized or decentralized solutions may be considered, influencing the performance of the Fault Detection, Isolation and Restoration (FDIR) algorithms [3]. **Table I** presents a comparison between three different Self-Healing schemes.

Table I. Comparative analysis of Self-Healing schemes.

Centralized	Semi-Decentralized	Decentralized
Dispatch Centre	**SSC**	**IED**
DMS/OMS	**micro-DMS**	**peer-to-peer GOOSE**
Any type of RTU	Any type of RTU	Specific RTU
High wide area scalability	Medium wide area scalability	Local area scalability
Slower response time	Average response time	Faster response time
High complexity	Medium complexity	Low complexity
Any type of remote control	Any type of remote control	Distributed intelligence

Independently of the implemented architecture, a Self-Healing solution includes a component layer, composed by the network physic infrastructure, a bidirectional and integrated information and communication layer, and a function layer, which includes different processes – monitoring, warnings analysis, decision-making and control actions.

Concerning the different power switchgear solutions available, the most suitable solution for Self-Healing implementation in overhead distribution networks comprises switchers and reclosers [4]. As a latest technology, reclosers imply higher CAPital EXpenditures (CAPEX) and OPerational EXpenditures (OPEX), but are capable of interrupt fault currents and perform a sequence of opening and reclosing actions thus reducing the ENS, the number and duration of permanent and temporary interruptions.

Taking into account the implemented architecture and the features of the component layer at the process, field, station and operation level, the assessment over the optimal number and location of power switchgear devices depends on several factors, such as reliability, network physical characteristics, CAPEX and OPEX of the adopted solution. Due to the influence of technical and economic aspects, a Cost-Benefit Analysis (CBA) must be performed considering both aspects.

METHODOLOGY

To assess the optimal deployment of reclosers in overhead distribution networks a methodology is used to define their optimal number and location, comprising a technical assessment of the service restoration feasibility through network reconfiguration and an economic assessment based on a CBA over the devices life cycle.

The distribution network is regarded as a Distribution Grid Area (DGA), i.e. an operational area defined by a range of primary substations and their feeders, with the possibility of automatic reconfiguration [3]. Moreover, the presence of Renewable Energy Sources (RES) within the DGA may be taken into account, with influence in the network constraints faced during the network reconfiguration process for service restoration.

The techno-economic analysis considers improvements in several reliability indices, such as the ENS, the System Average Interruption Frequency Index (SAIFI), the System Average Interruption Duration Index (SAIDI), and the Momentary Average Interruption Frequency Index (MAIFI), as well as the curtailment reduction with the deployment of each additional recloser. In addition, the investment costs effectiveness of the solution achieved in each iteration is assessed using economic indicators, such as the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback Period (PbP).

In [5] the main features and assumptions of the methodology are presented in detail. Compared to the method described in [5] the most significant improvements proposed are related with the following details on the steps of the methodology:

<1> The network model considers six load factor scenarios – two seasons (i.e. summer and winter) and three periods of the day (i.e. peak, non-peak and valley) – and six RES output scenarios – the same two seasons and three power output levels (i.e. 100%, 50% and 0% of the nominal power);

<4> The reclosers' optimal location within a feeder is assessed by applying an exhaustive search method to the problem, which will be searching for the optimal solution in each iteration *n*, i.e. the optimal location of *n* reclosers deployed in each zone of the network. Moreover, the reliability improvements are quantified considering the additional contribution of the economic benefit achieved with the curtailment penalty reduction;

<8> The proposed sensitivity analysis is performed over the optimal solution, where its robustness to key technical and economic parameters is assessed. The main parameters evaluated in this step are: the values of ENS and curtailment penalty; the load growth rate per year; and the influence of the QoS zone, i.e. the reference patterns for the total average number and duration of long interruptions during a predefined period of time, normally one year.

Figure 1. summarizes the main steps of the methodology.

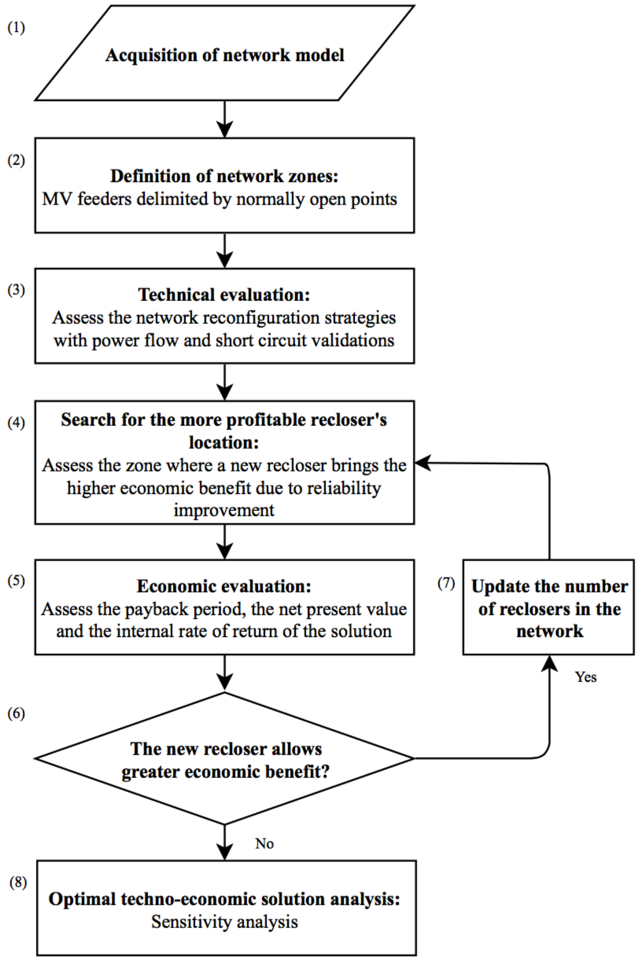

Figure 1. Optimal recloser deployment – methodology flowchart [5].

The optimization process considers different possible locations for the reclosers' deployment and for the faults occurrence, framed in several load and RES' output scenarios.

A case study in a real Portuguese MV (15 kV) overhead distribution network [5], is used to validate the methodology, based on a techno-economic analysis of the benefits achieved due to reliability and quality of service improvements.

CASE STUDY: SYNOPSIS AND RESULTS

Techno-Economic Assessment

Assessing the network reconfiguration strategy for service restoration will ensure that the technical limits are preserved, i.e. voltage on every bus within 0.9 and 1.1 pu, and no overloaded lines.

Due to the deployment of each recloser the network's reliability will improve and comparing the values of the reliability indices calculated in each iteration will possible to assess the economic benefit of the deployment of each recloser. Moreover, the following parameters must be considered: unitary values for the compensations related with the duration and number of interruptions; unitary value for the kilowatthour of energy not supplied – V_{ENS}. These parameters will affect the Total Compensation (TC) to be paid to the customers due to excessive number and duration of long interruptions, as well as the Cost of Energy Not Supplied (CENS) and the Incentive to Quality of Service (IQS). All the parameters used where adopted from [5]. For the curtailment penalty the considered value is, $V_{curtailment}$ = 70 €/MWh, the reference value applied in Portugal, which will affect the Costs of Curtailment (CCurtailment).

The solution achieved in each iteration represents the maximization of TC, CENS and CCustailment reduction and IQS increase. The total economic benefit achieved throughout the recloser's life cycle is opposed to the investment costs, CAPEX and OPEX, in order to assess the economic viability of the investment through the NPV, the IRR and the PbP.

Main Results

Base Case:

The optimal solution comprises 3 reclosers, deployed in the locations shown in **Figure 2**.

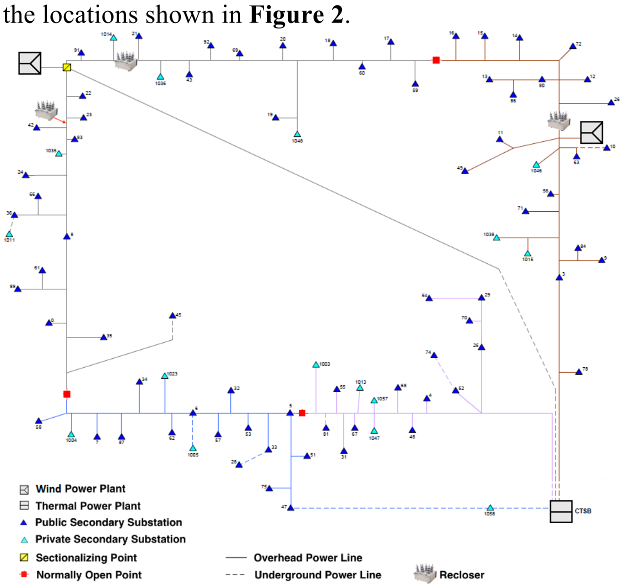

Figure 2. Case study network, base case optimal solution.

The Wind Power Plants (WPPs) identified in **Figure. 2** are not considered for the base case scenario and will be assessed on a latter step.

The economic assessment over the reclosers' life cycle reveals a NPV of approximately 25.9 k€ and a PbP of 8 years, as shown in **Figure 3.**, with a IRR of 18%.

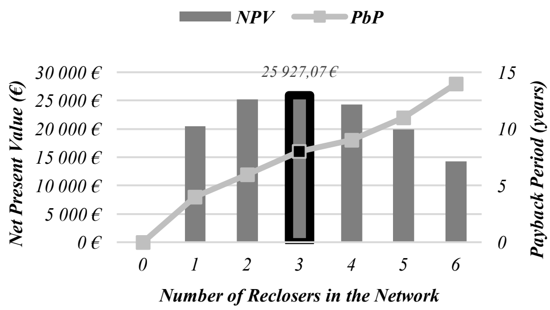

Figure 3. NPV and PbP evolution – base case.

The optimal solution for the base case presents the following ENS evolution: a reduction from 4.97 MWh – 0 reclosers in the network – to 2.78 MWh – 3 reclosers optimally deployed along the network.

Moreover, SAIDI is reduced in 47%, SAIFI is reduced in 50% and MAIFI is reduced in 29%.

RES Case:

Considering a scenario with RES deployed along the MV network – the WPPs identified in **Figure 2.** with, 4.25 MW (WPP on the left in **Figure 2.**) and 1.8 MW (WPP on the right in **Figure 2.**) of nominal power – the optimal solution comprises 3 reclosers, and the economic assessment reveals a NPV of approximately 26.1 k€ and a PbP of 8 years, as shown in **Figure 4**.

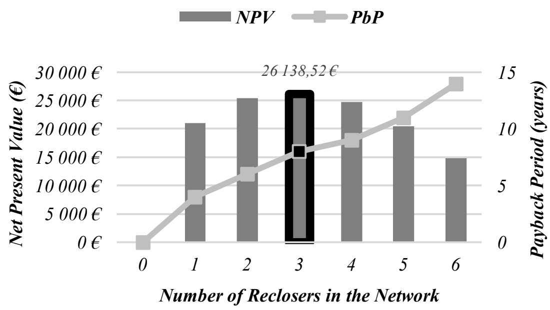

Figure 4. NPV and PbP evolution – RES case.

The results show the influence that RES have in the network's reliability. Considering RES, the NPV of the optimal solution increases, due to the capacity from the WPPs to support voltage along the feeders and prevent overloads after the network reconfiguration for service restoration, which will increase the load restored after FDIR.

The economic impact of the wind curtailment is also taken into account, once reclosers may help reducing the CCurtailment.

Sensitivity Analysis:

Value of ENS

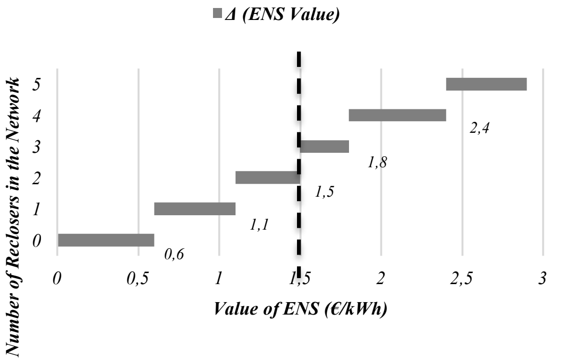

Figure 5. Influence of the V_{ENS} in the optimal solution definition.

Figure 5. shows the evolution of the optimal solution with the increasing of the value of ENS, which will influence the CENS and the IQS.
The V_{ENS} used in the base case is marked by the dashed line – 1.5 €/kWh – resulting in 3 reclosers optimally deployed along the network.

Load Growth Rate per Year

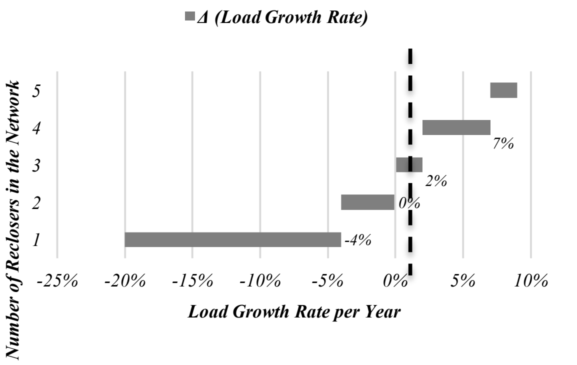

Figure 6. Influence of the load growth rate in the optimal solution definition.

Figure 6. shows the evolution of the optimal solution with the increasing of the load growth rate per year, during the reclosers' life cycle.
The *Load Growth Rate per Year* used in the base case is marked by the dashed line – 1% – resulting in 3 reclosers optimally deployed along the network.

Value of Curtailment

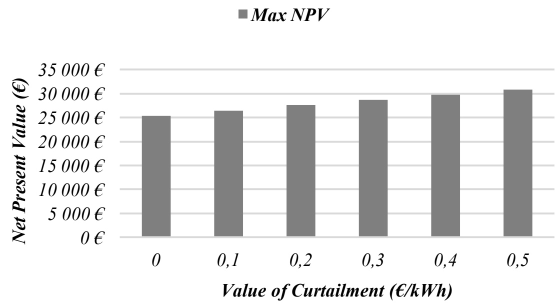

Figure 7. Influence of the $V_{curtailment}$ in the NPV of the optimal solution.

Figure 7. shows the evolution of the optimal solution's NPV with the increasing of the values of curtailment, which will influence the CCurtailment.
For all the $V_{curtailment}$ levels considered, the maximum NPV was achieved with an optimal solution of 3 reclosers.

Number of long Interruptions (NI)

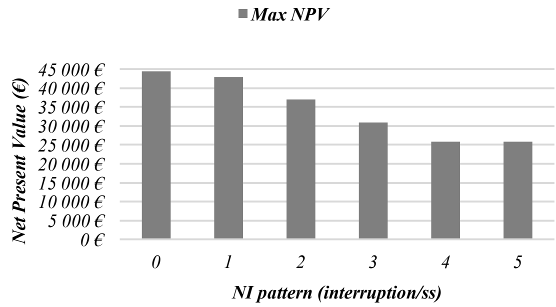

Figure 8. Influence of the reference value of the number of long interruptions in the NPV of the optimal solution.

Figure 8. shows the evolution of the optimal solution's NPV with the increasing of the reference pattern for the number of long interruptions per secondary substation in one year, which will influence the TC.
With an allowed *NI pattern* of 0 interruptions/ss, the optimal solution was achieved with 4 reclosers optimally deployed along the network. For all the other *NI* levels considered the maximum NPV was achieved with an optimal solution of 3 reclosers.

Duration of long Interruptions (DI)

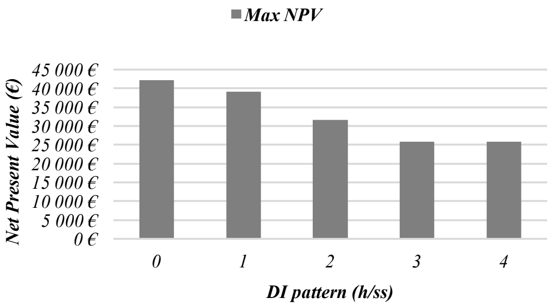

Figure 9. Influence of the reference value of the duration of long interruptions in the NPV of the optimal solution.

Figure 9. shows the evolution of the optimal solution's NPV with the increasing of the reference pattern for the duration of long interruptions per secondary substation in one year, which also will influence the TC.
With an allowed *DI pattern* of 0 h/ss, the optimal solution was achieved with 4 reclosers optimally deployed along the network. For all the other *DI* levels considered the maximum NPV was achieved with an optimal solution of 3 reclosers.

FINAL REMARKS

The advanced methodology assesses the optimal deployment of reclosers, considering their number and location, leveraging Self-Healing in distribution networks.
The techno-economic analysis considers the presence of RES, which may influence the network constraints, mainly related with the need of constantly maintain the voltage and current magnitudes within their operational limits.
The case study results show that the optimal deployment of reclosers, properly coordinated and allowing advanced Self-Healing schemes, improves reliability, while mitigates the impact of permanent and temporary faults and provides power distribution security, with economic benefits for the customers and the DSO.
Moreover, some improvements to this method may be considered, in order to obtain even better and more realistic results.
Previous power switchgear technologies already deployed in the network may also be considered, as their location influence the optimal deployment of the reclosers – number and location.
Other Distributed Energy Resources (DER) apart from RES, such as Battery Energy Storage Systems (BESS), may also be considered and even optimized for service restoration, in terms of capacity and location.
The economic analysis may take into account the possibility of the network's expansion along the reclosers' life cycle, i.e. new secondary substations added or old ones deactivated, which at least will influence the economic feasibility of the total investment – NPV, PbP and IRR.
The method used to assess the reclosers' optimal location may also be updated. Despite from this tool be used only for reliability and planning assessments, made offline, there are several methods which may be more suitable for application to this optimization problem, significantly reducing the computing time and effort. Metaheuristics, such as evolutionary programming or genetic algorithms, may be considered.

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