Assessing the Impact of Investments in Distribution Planning

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***Abstract*— The expansion and development of the electricity distribution grid is a complex multicriteria decision problem. The planning definition should take into consideration the investment benefits on the security of supply, quality of service, losses, as well as in other network features. Given the variety of assets and their context-dependent effects, estimating their global impact is very challenging. An additional difficulty is the combination of different types of benefits into a simple and clear portrayal of the planning alternatives. This paper proposes a methodology to estimate the benefits of distribution investments, in terms of five features: security of supply, quality of service, network losses, operational efficiency and new services. The approach is based on the adoption of objective and measurable indicators for each feature. The approach was tested with real data of Portuguese distribution grids and the results support the adopted approach and are being used as a decision-aid tool for grid planning.**

***Index Terms*—Distribution system planning, Security of supply, energy losses, Operational costs.**

I. Nomenclature

DN	Distribution network
DSO	Distribution System Operator
DTC	Distribution Transformer Controller
ENS	Energy Not Supplied
HV	High Voltage
LV	Low Voltage
MAIFI	Momentary Average Interruption Frequency Index
MV	Medium Voltage
NE	Network Efficiency
NS	New Services
OE	Operational Efficiency
QoS	Quality of Service
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SoS	Security of Supply
TCM	Transformer Capacity Margin
TIEPI	Equivalent interruption time of the installed capacity in MV/LV substations (used in Spain and Portugal) [1]

II. Introduction

The last decades witnessed important changes in the architecture and complexity of electricity distribution systems. Two key factors for these changes were the advent of a free market environment and the expansion of distributed generation. The current and next future factors of change are the transition to smart grids, the dissemination of electric vehicles and microgeneration and the development of energy communities. Not only distribution systems are changing but also the rate of change is increasing.

The classic methodology for distribution systems planning was a rather straightforward process based on long-term forecast of load growth, followed by a convenient upgrade of network capacity or network expansion. This approach is no longer appropriate [1][3]. In fact, the new energy resources, like distributed generation, storage and electric vehicles, are able to change the power flows and the diagram shapes, changing peak loads or creating new ones.

Other factor to be considered is the DSO organizational culture and its *modus operandi*. These aspects define the real background of all company projects, conditioning the investment priorities, the human resources management and even its long-term planning strategy.

Considering these challenges, it was launched the ImpInv project in a collaboration with EDP Distribuição (a Portuguese DSO). The main goal of this project was to estimate the impact of planning investments, in terms of quality indices (losses, END, SAIDI, etc.) and the monetization of the associated benefits. This paper describes the first part of the project: estimation of the investments impact on the quality features of the distribution network. Due to space limitations, only the results of SoS and QoS are presented in this paper.

The rest of the paper is organized as follows Section III presents the framework of the developed research and Section V describes the adopted methodology. Section VI exposes the most relevant results and, finally, Section VII synthetizes the main conclusions of the work.

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III. CONTEXT

According to the current Portuguese legislation concerning the electricity sector (Decree-Law 215-A/2012) [1], the Distribution System Operators (DSO) are required to propose the regulator a Plan for Development and Investment in the Distribution Network (PDIDN) [2]. This plan should be designed for a time frame of five years and updated every two years, based on the technical characteristics of the network and its current and predicted supply and demand. This DSO obligation was the main driver of ImpInv project.

At EDP Distribuição, investments in the distribution network are generally classified according to their potential contributions to the following strategic features:

1. Security of Supply (SoS)
2. Quality of Service (QoS)
3. Network Efficiency (NE)
4. Operational Efficiency (OE)
5. New Services (NS)

These features refer to different aspects of the power grid quality[1]. The last one (NS) concerns the benefits of installing intelligent network monitoring and control devices (such as smart meters or distributed control devices), which will provide more and better information on network status and more effective control actions. NS will support the establishment of energy communities and local energy markets, the estimation of technical losses, the identification of consumer anomalies / fraud, the exploitation of storage units, and others.

The medium-term planning of the development of the distribution network, in particular the preparation of PDIDN, takes these factors into account, aiming at combining the different features into a harmonized investment program. PDIDN concerns the HV and MV network levels; up to 2020, LV was not considered in PDIDN.

However, investment planning optimization is a multi-objective problem that requires the characterization of different types of initiatives (e.g. network development, primary and secondary substations and their connections, etc.) and its potential impacts on investment features (e.g. security of supply, quality of service, etc.). In practice, the DSO tries to identify a balanced combination of good investment initiatives with the need of other priority actions. In the specific case of EDP Distrbuição, the final selection phase includes the comparison of a set of alternative investment scenarios in terms of cost and network benefits.

The characterization of the impacts of investments is fundamental to highlight the technical rationality of the proposed plans, and thus for decision-making on the most appropriate investment scenarios. The ImpInv project [1] aims at developing models and tools to estimate the impact of different investment scenarios in these features. A second objective is to monetize the benefits of each feature, in order to support the investments rationality. The present paper is focused in the first ImpInv goal.

In summary, the tool to be implemented should provide estimates of the SoS, QoS, NE, OE and NS, features depending on a number of selected investments [1]. The DSO usually proposes three alternative investment scenarios, that specify different amounts assigned to the various investment programs each year, i.e. the DSO proposes, in each scenario, a set of projects to be carried out in the PDIDN time horizon. The regulator then decides which of the three scenarios should be implemented.

The studies and results reported in this document concern the definition of models to estimate the impacts of the investments on the different features in terms of technical indicators. The specificity of each feature requires each case to have a very own approach, as detailed in Section V.

IV. DATA

The data used in this study was provided by EDP Distribuição and can be organized in three groups: the investment amounts, the adopted quality indices and the DN characterization variables:

<u>Investment data</u>

- Historical values by program from 2008 to 2018;
- Planned investments for 2018;
- Three investment scenarios for the next PDIDN (from 2019 to 2023);

<u>Quality indices</u>

- ENS, from 2008 to 2018;
- SAIDI, TIEPI, MAIFI and SAIFI – annual values from 2008 to 2018. MAIFI only available after 2011;
- Extensive lists of all individual incidents in the TCM network from 2008 to 2018;
- Losses, from 2008 to 2018;

<u>DN characterization</u>

- Evolution of the DN energy consumption;
- Maximum power flow at each substation transformer as well as its nominal ratings;
- Three scenarios of demand evolution, for the PDIND period (2020-2025);
- Projection of the evolution of the number of consumers from 2020 to the 2050;
- Projection of the evolution of distributed generation from 2020 to the 2024;
- Historical data concerning the installation of advanced sensing and automation devices, from 2009 to 2018.

V. METHODOLOGY

A) Introduction and general approach

One of the pillars of the developed methodology was the adoption of objective and measurable quality indices for the characterization of the distribution network (DN), aiming at quantifying the impacts of investment scenarios on the selected features (SoS, QoS, NE, OE and NS).

Fig. 1 outlines the interactions between the main variables considered in the proposed approach. The leftmost block (Investment) reflects the DSO enterprise culture that allocates the investments into several types of programs (type 1: network development; type 2: network automation; etc.). The impact of each program in each feature is specified by a matrix of contributions (MC in the figure), which specifies the weight (percentage) of each program on each feature. These weights are provided by the analysis of the historical impact of the projects within each program.

The Regression block, in Fig. 1concerns the inference of functional relations between the investment features and the strategic objectives, i.e., the indices selected to classify the state of the DN. This allows the estimation of the evolution of the DN quality indices throughout the plan, depending on the considered investment scenarios.

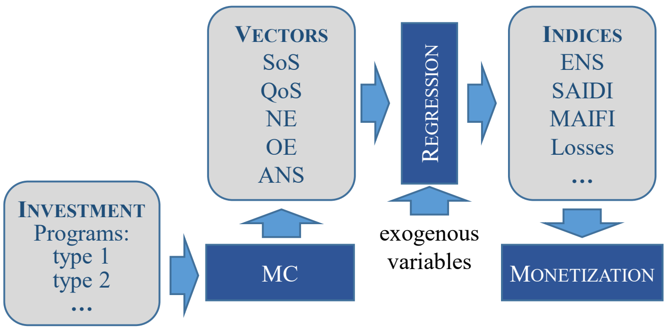

Figure 1. Main steps of the proposed methodology

Most indices depend not only on the investment programs but also on the current state of the DN and other exogenous variables. For instance, expected losses depend not only on the investment on lines reinforcement programs but also on the losses that occurred in the previous year and on the expected energy consumption (higher load means higher losses).

B) DN quality indicators

In this study the SoS is characterized by the ENS index, as any problems in this feature will result in interruptions of the supplied energy.

The QoS is mainly characterized by the SAIDI and TIEPI indices, accordingly to the current Quality of Service Code. SAIFI and MAIFI are considered as complementary indices.

The NE is represented by the percentage of technical losses in the distribution network regarding the demand in line with the indications of the Regulatory Agency.

The OE feature is characterized by the following indicators:

- EAutDN – MV network automation index. This indicator is proportional to the number of control elements in the network (e.g. DTC [10]);
- TC Points – number of telecommand points providing insight on the network monitoring level;
- TFI – total interruptions frequency, SAIFI + MAIFI;
- RIL – ratio between long interruptions (SAIFI) and total interruptions (SAIFI + MAIFI);
- SCADA Orders Effectiveness – this indicator measures the efficacy of the automatic maintenance requests created by the SCADA system. This index is related with the TC Points;
- ROM – ratio between manual and total maintenance requests (diminishes with automation increase).

The NS feature analyzes the benefits of installing intelligent network monitoring and control devices. Most of these investments are made at LV networks, but PDIDN only addresses the costs and benefits at MV and HV levels. Consequently, the NS benefits need to consider how the investments in this feature (mainly in the LV grid) impact on the MV and HV networks.

C) Summary of Indices Estimation Processes

The general strategy used to construct a given index estimation model comprises the following main steps:

1. Analysis of the historical evolution of the indices;
2. Identification of potentially influential factors.
   a. For the SoS feature, it was assumed that ENS depends mainly on the network capacity to supply the loads. Hence, the ENS depends on the current ratio between the load peak and the nominal capacity of each HV/MV and MV/MV transformer, on the annual load growth and on the diagram shape;
   b. For the QoS feature, it was assumed that the indicators SAIDI, TIEPI, SAIFI and MAIFI would depend on the state of the network (represented by the previous instances of these indicators), on the investment directed to the improvement of QoS and on the expected energy flowing in the network along the period addressed by the PDIDN period;
   c. For the NE feature, it is assumed that the global DN technical losses depend on consumption, on the distributed generation and also on the investment in loss reduction programs;
   d. The benefits from the OE feature denote gains in downtime and lower costs with maintenance teams. The OE model aims at relating the amount of automation elements with the OE gains;
   e. Finally, the procedure adopted to characterize the benefits of investments in the NS feature is based on the assumption that these new services will induce changes in consumption. For this case, a sensitivity analysis was performed to characterize the evolution of demand (and the peak) as a function of the investment in this feature.
3. Performing regression analysis. Several types of models and different types of transformations (exponential, logarithmic, etc.) of the input variables were tested, in order to emulate the different types of effects. In the end, the models we selected that best fit the available history (lowest mean squared error), but, at the same time, that reflect dependencies with a rational physical meaning.

D) Estimation of the quality indices

1) Security of Supply (SoS)

As mentioned in the previous section, the ENS is a natural index to quantify the SoS state. However, SoS is a primary concern of the DSO, who aims at ensuring a 100% SoS, i.e., the network planning is developed taking into consideration the current relation loads/capacity in the main network components and the expectation of load growth. Besides, a N-1 security criterion is considered on a regional basis. According to internal

TABLE I. MATRIX OF CONTRIBUTIONS

Investment type	Investment programs (HV and MV)	Contribution SoS	QoS	NE	OE	NS	Other
Mandatory	Excluding meters	85%	5%	5%	5%		
	Only meters						100%
Structuring	Network development	20%	30%	45%	5%		
	Acquisition of terrain for substations	20%	30%	45%	5%		
	QoS improvement	7%	80%	6%	7%		
	Automation and telecommand of MV network		90%		10%		
	Environment promotion						100%
	Risk Mitigation of Critical Infrastructure Operation						100%
	Substations modernization		70%		30%		
	Intelligent telecommunications operation		70%		20%	10%	
	Loss reduction	20%	20%	55%	5%		
	Installation of AMR in secondary substations				20%	80%	
	Project Inovgrid		10%		5%	85%	
	Other innovation projects		10%		5%	85%	
Normal program	Renovation and Rehabilitation of Degraded Assets	10%	60%	10%	20%		
	Maintenance of security bands against forest fires		30%				70%
	Extraordinary beneficiation	10%	20%	10%	40%		20%
	Installation of neutral reactances		95%		5%		
Urgent routine	Secondary substations connection	60%	10%	20%	10%		
	Urgent investment program	10%	20%	10%	40%		20%

planning rules of EDP Distribuição, if one substation goes out of service, the remaining ones in the same zone should be able to feed the total load, with a margin of, at least, 5%. Currently data is being gathered to related directly investments with ENS.

In this case, the adopted methodology is structured in the following steps

1. Compute the SoS margin for each substation transformer – variable TCM in (1). In this expression, PN represents the nominal power of each transformer. TCM is calculated for each year in the study horizon (30 years), based on the estimation of the annual peak power evolution.

$$TCM_{Year}[\%] = 1 - \frac{abs(Peak\ power_{Year})}{PN_{Year}} \quad (1)$$

The absolute value in the numerator is considered because, in some cases, the maximum peak power is negative due reverse power flows caused by the large penetration of distributed generation at some points of the network.

At this stage, the transformers with TCM below a minimum threshold, specified by EDP Distribuição at 5%, were identified, implying a cut-off, paid by the cost established by the Regulatory Agency for ENS. The histogram of Fig. 2 presents a general portrait of the HV/MV transformers rated load factor (peak load / nominal power).

2. Compute the value of TCM in [MVA]:

$$TCM_{Year}[MVA] = abs(PN_{Year} - Peak\ power_{Year}) \quad (2)$$

3. Estimate $h_{critical}$, the number of critical hours in each year – it corresponds obtain the number of hours for which the transformers have $TCM/PN_{Year} < 5\%$.

The load duration curves of Fig. 3 were based in the typical Portuguese HV diagrams. The number of critical hours ($h_{critical}$) for each transformer is determined as follows:

a. Estimate the effective capacity Ce of each transformer in each year:

$$Ce_{Year}\ [MVA] = PN_{Year}\ [MVA] \times 0.95 \quad (3)$$

$$Ce_{Year}\ [\%] = Ce_{Year}\ [MVA]\ / Peak\ power_{Year} \quad (4)$$

b. Use the load duration curve of Fig. 3 to estimate $h_{critical}$ – the number hours the demand is above Ce[%]. This assessment is exemplified in Table II.

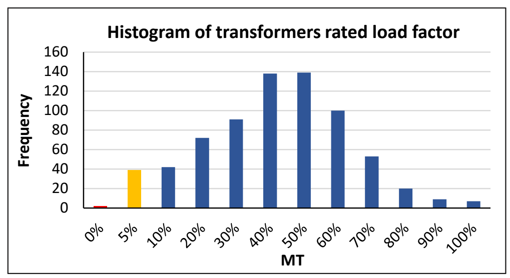

Figure 2. Histogram HV/MV transformers load to capacity ratio

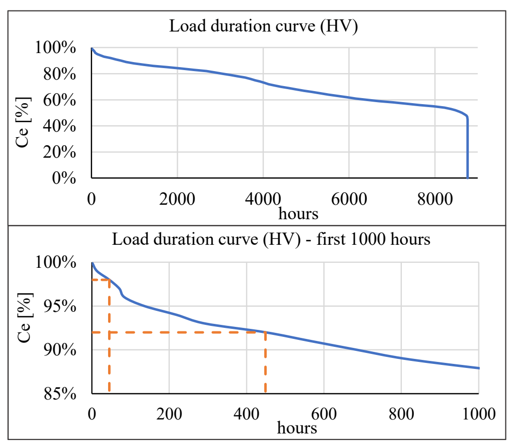

Figure 3. Load duration curves of a HV/MV transformer (the bottom chart is a zoom of the top one for the highest 1000h)

TABLE II $H_{CRITIVAL}$ CORRESPONDING TO EACH CE [%].

Ce[%]	HC (hour)
(…)	(…)
90%	685.3
91%	566.0
92%	449.0
93%	293.0
94%	218.5

Ce[%]	HC (hour)
95%	135.8
96%	84.3
97%	70.8
98%	45.0
99%	13.0
100%	0

The projection of $h_{critical} \times MT_{Year}$ provides an estimation of the ENS within the PDIDN period.

2) Quality of Service (QoS)

The indices that characterize QoS are: SAIDI, TIEPI, SAIFI, MAIFI. The estimation of these indices was based on the analysis of their historical evolution and their relationship with the potentially influential variables.

The assumed regression model was specified according to (5), here exemplified for the SAIFI indicator:

$$SAIDI_n = \propto_1 \cdot SAIDI_{n-1} + \propto_2 \cdot log\left(Inv_{QS_{n-1}} + C_{Aten}\right) + \propto_3 \cdot \Delta E_n + \propto_4 \quad (5)$$

In this expression, n refers to the year, Inv_{QS} is the investment in the feature QoS, C_{Aten} is a parameter to adjust the log term and to avoid log(0). Besides, C_{Aten} attenuates the decrease of SAIDI when the investment decreases considerably; ΔE_n is the variation of the distributed energy from the year n-1 to the year n, and α_1, α_2, α_3, α_4 are model parameters.

The proposed model was based the following reasoning:

- The $SAIDI_n$ in a given year depends on the performance of the DN in the previous year $SAIDI_{n-1}$;
- The gain in the quality indices is not proportional to the investment. In effect, if the investment effort required to reduce, for example, 1 min of SAIDI is Inv1, then the investment required to reduce 2 min will be higher than 2×Inv1. That is why the logarithmic function was used in order to reflect the fact that the cost of DN quality improvement is progressively higher;
- The sensitivity analysis of historical DN quality indices with respect to energy consumption showed that these variables are related. Although there is no direct causality between the variable Energy and the number and duration of interruptions, our interpretation is that these variables most likely have a common cause. The incidents analysis reveal that the years having a higher number of incidents (interruptions) are actually the years with higher energy consumption; maybe more rigorous winters (larger periods of cold and intense rain and wind) are the common cause of more interruptions and higher consumption;
- The model parameters (α_1, α_2, α_3 and α_4) should be constrained to intervals, in a way that the model physical meaning is preserved. For instance, the parameter α_2 should be negative – higher investments are expected to decrease SAIDI; the parameter α_1 should be positive to represent the relation of the DN quality index between year n and year n-1; the parameter α_3 is also positive, as referred in the previous point, it translates the increase of indices with energy increase; finally, the parameter α_4 should be positive, because it symbolizes the DN quality degradation – if nothing is done (invested), the quality indices will worsen.

These constraints were considered in the regression procedure, in which the optimization goal was to estimate the index by minimizing the mean squared error between the real and estimated values.

As an illustration, the top of Fig. 4 presents the historic and estimated values of the SAIDI index, for the three investment scenarios considered in the PDIDN. The confidence margins for Scenario 2 in the bottom graph were estimated by multiple sampling of the incidents database to emulate the stochastic nature of these events. The indices were added on a daily basis and an annual diagram was defined. This happen between 2009 and 2018, in order to understand the evolution of the index over the period.

Days were randomly selected until half of the annual diagram is completed and subsequently multiplied by two in order to obtain the annual diagram. Then, the diagrams were ordered to extract the minutes corresponding to the 5% and 95% best cases. The difference between the result for these levels and the historical value (50%) allows us to determine the annual evolution of this band and to project it until the end of the PDIDN based on a linear regression.

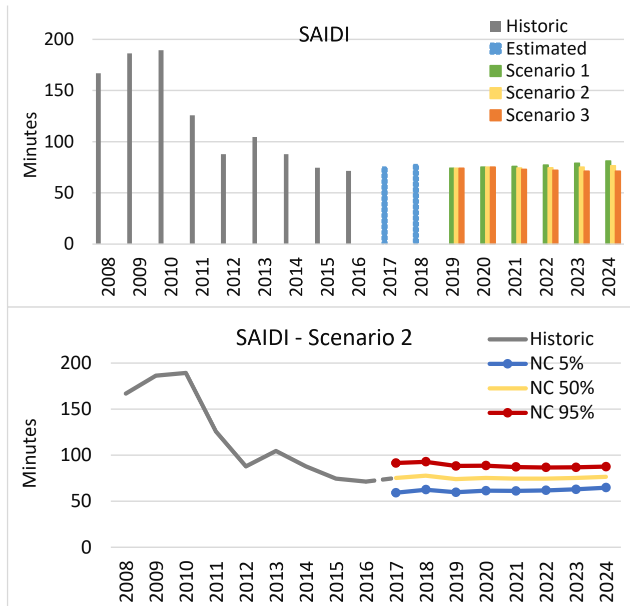

Figure 4. Historic and projected values of SAIDI (top) and cinfidence levels (NC) 5%, 50% and 95% for scnenario 2 (bottom)

VI. Conclusions

This paper describes a methodology to estimate the impact of investments in the electricity distribution network, in terms of indices used to characterize the network quality state. The application examples described concern the security of supply and the quality of service, although the whole project also include the other aspects (network losses, operational efficiency and new services).

The main results obtained in the previous PDIDN show that the proposed approach can produce good estimates of the quality indices of the distribution network.

The DSO has adopted this tool, which is currently used as a decision-aid instrument to design the medium-term plan concerning the distribution grid investments.

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