Quality and management of a MV-LV grid: analysis of the power network and optimization considering new strategies

Catarina e Santos Bordalo
DEEC
Instituto Superior Técnico
Lisbon, Portugal
catarina.bordalo@tecnico.ulisboa.pt

***Abstract*—In a world where the fight against climate change presents itself as a pressing issue, it has never been more pertinent to address energy efficiency as a measure of mitigation of global warming's consequences. Therefore, power losses are regarded as an energy efficiency indicator, and four optimization strategies are selected: reactive power compensation, Distribution Energy Resources (DERs), adjustment of the transformers' taps, and topological reconfiguration. An investigation concerning the applicability of these four optimization strategies for Sintra's Military Complex power network is proposed, taking into account the economical aspects of the implementation of such measures. Therefore, a methodology was set, where the formulation of the optimization problem, the definition of power consumption scenarios, the development of a program based on NSGA-II, and the decision-making process based on the MP Approach can be highlighted. The execution of this methodology indicates that the considered optimization strategies cannot reduce power losses in Sintra's Military Complex power network for any scenario, which also implies that the study of the economical strand of these strategies could not be performed properly. The limitations of this investigation were identified concerning the carried-out stages. Moreover, some suggestions for future work were drawn based on the results of this investigation and the acknowledgeable limitations.**

***Index Terms*—Distribution power network, Power losses, Multiobjective Optimization, Genetic algorithms, Decision-making process**

I. Introduction

Electrical energy can be considered indispensable for the majority of society's social and economical needs and the infrastructure that allows its production, distribution, and consumption is the electrical grid. Given its importance, it is advised that the power grid is updated according to the most recent technological standards, being energy efficiency one of them [1].

Nowadays, the efficient usage of electrical energy is of rising importance due to the emerging attention related to climate change. Therefore, several players in the energy sector are starting to consider the energy efficiency vector. Energy efficiency can be defined as the capacity of using a lesser quantity of energy for the achievement of the same purpose. Therefore, an increase in energy efficiency can be related to the electric power reduction needed for the power network's operation, which can be achieved by reducing power losses [2], [3].

This work takes power losses as an energy efficiency indicator and aims to study the extent of its minimization in the electrical distribution network of Sintra's Military Complex. For this purpose, four optimization strategies are considered: reactive power compensation, implementation Distribution Energy Resources (DER), adjustment of transformer' taps, and topological reconfiguration [4], [5].

The theoretical outline of the adopted methodology is adapted from the MP Approach as described in [6]. This methodology includes the resolution of the optimization problem, which can be attained through a computational tool. A program is developed based on NSGA-II (as referred to in [7] and [8]) where the evaluation of the optimization strategies can be completed. Given that the adoption of the optimization measures implies some operational and economical restrictions, the NSGA-II based algorithm was adapted to consider them through penalty functions, as in [9].

This extended abstract aims to present a synthetic state-of-the-art review, followed by the description of the most important methodological steps, as developed in the MSc Thesis with the same title. In addition to these, the results of the investigation are discussed and the key conclusions are presented.

II. Optimization of Sintra's Military Complex power distribution network regarding energy efficiency

A. Modeling Sintra's Military Complex power distribution network

Sintra's Military Complex is a Portuguese Air Force (PoAF) military unit that comprises the Portuguese Air Force Academy, the Air Museum, and the Air Base N°1. One of the factors that allow the fulfillment of its operational purpose is its power distribution network, which is shown in Figure 1.

This power network has a radial configuration and operates at Medium Voltage (MV) - with a nominal voltage of 10 kV - and at Low Voltage (LV) - with a nominal voltage of 400

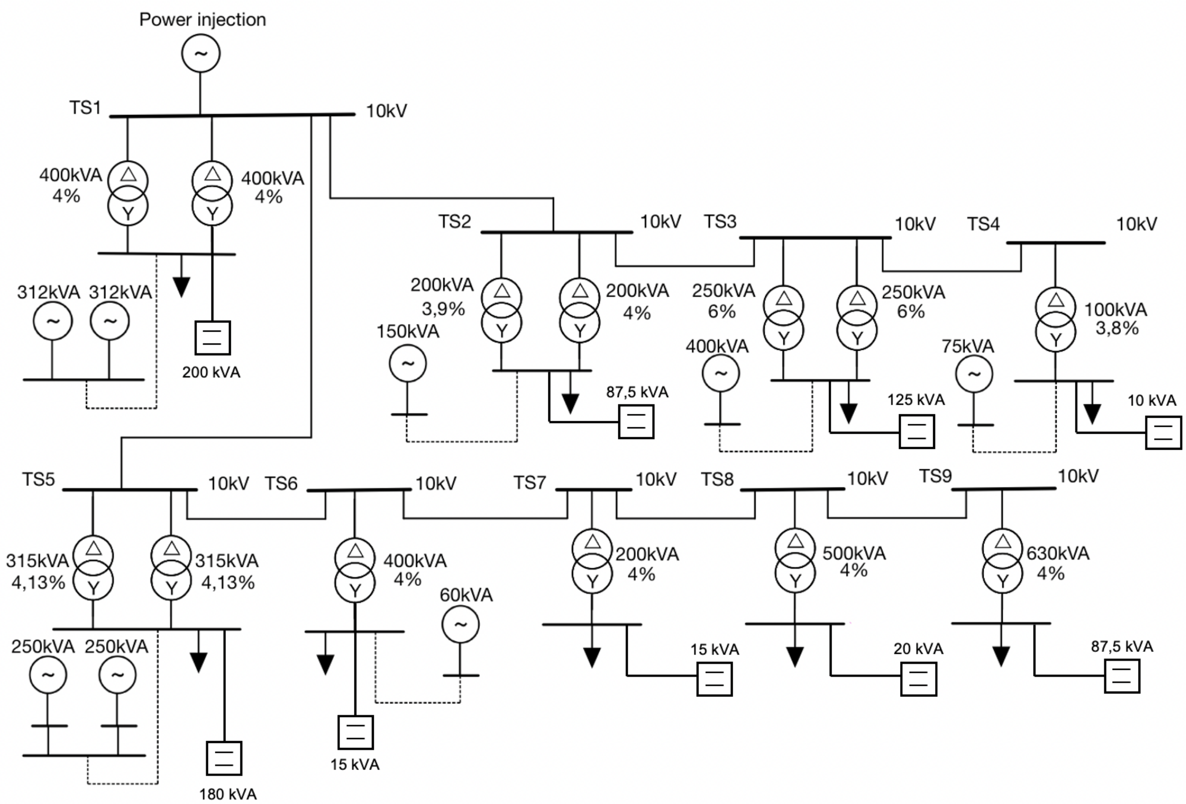

Fig. 1. Equivalent network of Sintra's Military Complex power distribution network

V. As it can be identified in Figure 1, there are nine Transformer Stations (TS) that are connected by LXHIOZ1(cbe,frt)-R1x120mm2 underground power cables. Figure 1 also shows that each TS has one or two Δ/Y tap-changing three-phase transformers. Each LV bus of the TS connects to a capacitor bank that acts on reactive power compensation. Each TS is also equipped with a backup generator, although its operation is not considered in this investigation.

The most relevant components of this network are power lines, transformers, and capacitor banks. According to [1], these components can be represented by the following electrical models:

1) power lines: π equivalent model of the power line;
2) transformers: π equivalent model of the tap-changing transformer;
3) capacitor banks: admittance Y^{bc} associated with the injection of reactive power in the grid;
4) loads: modeled by a null elasticity.

These models alone represent only the correspondent components but not the operation of the power network. Hence the link between these models can be accomplished by a power flow analysis.

According to [1], this analysis can be described in three main stages: formulation of the mathematical model of the grid, specification of each bus type, and computation of the variables of interest.

The first step is based on the application of Kirchoff's laws regarding the connection between buses that are modeled by a π model; these relationships can be characterized by the Equation 1, where $\mathbf{S}$ is the injected apparent power, $\mathbf{V}$ is the complex voltage in each bus and $\mathbf{Y}$ is the admittance matrix.

$$\left[\frac{\mathbf{S}^*}{\mathbf{V}^*}\right] = [\mathbf{Y}]\,[\mathbf{V}] \tag{1}$$

For a power line, the elements of the admittance matrix $[Y]$ can be calculated with the Equations 2 and 3, in which $\mathbf{Y_k}$ and $\mathbf{Z_k}$ corresponds to the admittance and impedance of the considered model, respectively, and i and j regard two connected buses.

$$\mathbf{y_{ii}} = \sum_{j=1;j\neq i}^{n} \left(\frac{\mathbf{Y}_k}{2} + \frac{1}{\mathbf{Z}_k} \right) \tag{2}$$

$$\mathbf{y_{ij}} = \mathbf{y_{ji}} = -\frac{1}{\mathbf{Z_k}} \tag{3}$$

However, the computation of the elements of the admittance matrix $[Y]$ that are characterized by transformers depend on its position on the matrix:

- the diagonal element y_{ii} of $[Y]$ is the sum of $\frac{1}{m^2 \cdot \mathbf{Z_{cc}}}$ and the Equation 2, where $\mathbf{Z_{cc}}$ is the short circuit impedance of the transformer;
- the diagonal element y_{jj} of $[Y]$ is the sum of $\frac{1}{\mathbf{Z_{cc}}}$ and the Equation 2;

- the non-diagonal element y_{ij} is equal to y_{ji} and it can be computed throught Equation 4, in which m is the transformer ratio.

$$\mathbf{y_{ij}} = \mathbf{y_{ji}} = -\frac{1}{m \cdot \mathbf{Z_{cc}}} \quad (4)$$

At last, capacitor banks alter the admittance matrix because the admittance Y^{bc} must be added to the diagonal element y_{ii} corresponding to the bus that has this equipment installed.

The second step involves specifying each bus type. There are three types of buses: reference bus, PV bus, and the PQ bus. The reference bus is considered to be the reference for the grid, as its designation suggests; the PV bus is associated with voltage control, while the PQ bus is related to power consumption.

The last step - which is the computation of the variables of interest - requires the adoption of an iterative method that solves non-linear algebraic equations, since Equation 1 is of this type. The Newton-Raphson method is proved to be the reference in power flow analysis and its application is explained in depth in [1].

Additionally, the considered network analysis must also comply with the voltage and current stability limitations, according to Equations 5 and 6, respectively.

$$V^{min} \leq V_i \leq V^{max} \text{ for each node } i \quad (5)$$

$$I_{ij} \leq I_{ij}^{max} \text{ for each branch } ij \quad (6)$$

The power flow analysis aims to compute the variables of interest of a certain network, which are generally the modulus and the argument of voltage in each bus. These variables allow the computation of other variables that may be of interest, such as power losses. Power losses S_{losses} are characterized by equation 7.

$$S_{losses} = \sqrt{P_{losses}^2 + Q_{losses}^2} \quad (7)$$

These losses can be parted into active P_{losses} and reactive power losses Q_{losses} - as it is on Equation 7. These variables can be computed by Equation 8, where G_{ij} and B_{ij} represent the real and imaginary part of the element ij of the $[Y]$ matrix.

$$\begin{cases} P_{losses} = G_{ij}[V_i^2 + V_j^2 - 2V_iV_jcos(\theta_i - \theta_j)] \\ Q_{losses} = -(B_{ij} + B_{ij}^{'})(V_i^2 + V_j^2) + \\ +2B_{ij}V_iV_jcos(\theta_i - \theta_j) \end{cases} \quad (8)$$

B. Power losses and optimization strategies

According to [3], power losses can perform as an energy efficiency indicator. Therefore, it is important to define power losses and to determine which are the strategies that can mitigate their presence in power networks.

Power losses can be categorized in agreement with several classifications. However, the scope of this study aims to focus on technical losses in power lines and transformers for MV and LV voltage levels. This type of loss refers to the electrical energy converted to heat or noise during its transmission or distribution. In addition, technical losses can be calculated through several methods, depending on the available data regarding the power network. Since the amount of information about Sintra's Military Complex is scarce, the viable option for computing power losses resides in power flow analysis [1], [4].

Due to its importance regarding energy efficiency, power losses can be reduced by grid management strategies' application. An effective approach must comply with the condition set on Equation 9, where $\mathbf{S}_{losses}^{after}$ is the power losses after the implementation of an optimization strategy and $\mathbf{S}_{losses}^{before}$ is the power losses before such implementation.

$$\mathbf{S}_{losses}^{after} \leq \mathbf{S}_{losses}^{before} \quad (9)$$

The approaches considered in the scope of this investigation are reactive power compensation, installation of DERs, adjustment of transformer' taps, and topological reconfiguration.

At first, reactive power compensation intends to optimize voltage profiles in the network buses, which in turn reduces reactive power losses. The implementation of this approach can be accomplished by the installation of capacitor banks (that perform dynamic compensation) and its implementation is simpler in radial networks [4], [10]. In addition to the benefits concerning power losses, this strategy also allows a reduction in electricity billing if $tan\phi$ (where ϕ is the angle between V and I) complies with Equation 10 (from [11]), taking into account the periods defined in [12].

$$tan\phi \leq 0.3 \quad (10)$$

The second proposed approach for increasing energy efficiency is the implementation of a DER. A power network that has integrated a DER can profit in terms of supply and demand balance and reduction of the distribution distance - which contributes to the reduction of power losses [4]. Moreover, power losses can be characterized as a function of penetration as described in [14] and [15], hence there is an optimal point in terms of maximizing penetration and minimizing power losses. According to [10], penetration levels are acceptable for ring networks and problematic in radial networks, which can indicate that ring networks are more suitable for the implementation of DER technologies.

Due to the spatial and operational conjecture of Sintra's Military Complex, this solution consists of the installation of a photovoltaic system, with a $1:1$ proportion regarding the generated power Ppv and the power at the output of the power converter P^{inv}. Considering this ratio, the maximum installed power is limited by the contracted power $P_{contracted}$, as it is defined by Equation 11.

$$0.5 \cdot Ppv \leq P_{contracted} \quad (11)$$

Due to the geographical constraints, the area occupied by the DER must obide to Equation 12, which accounts for the spatial availability.

$$Apv \leq A_{available} \quad (12)$$

For this equation, $A_{available}$ is determined considering the available area for installation of this measure, whereas Apv can be defined by Equation 13. This equation provides an empyrical relationship between Ppv ans Apv based on the latest PoAF' projects.

$$Apv = 10 \cdot Ppv \quad (13)$$

Moreover, the third solution for the mitigation of power losses is the adjustment of transformer' taps. This strategy enables discrete voltage control at the bus level by changing the transformer ratio m in case of an imbalance, which can reduce power losses (as explained for the reactive power compensation measure) [4]. The criteria for the adjustment of the taps can be defined by Equation 5.

At last, the fourth strategy is topological reconfiguration. Considering its radial configuration, Sintra's Military Complex distribution network is more prone to power losses due to the extensive length of power lines and the possible inadequacy of the network present configuration for the load profiles. The proposed solution intends to reduce power losses by installing a power line between TS 4 and TS 9, thus reconfiguring the network into a ring configuration. Besides the advantage of reducing power losses, this configuration also allows an increased operation's reliability.

The implementation of these optimization strategies is achieved through the development and execution of projects. However, the related financial costs must be pondered due to budget limitations. Therefore, considering profitability criteria can be a useful tool in assessing the viability of a project - the payback period PR is one of these criteria. This criterion determines the period in which the investment costs are recovered. Generally, PR is limited by Equation 14, where t is set according to the responsible entity's perspective.

$$PR \leq t \quad (14)$$

Furthermore, PR can be defined by Equation 15, where $I(\mathbf{x})$ is the investment cost, $\sum CF$ is the sum of the cash flows and $years$ are the years in which the project will create a financial return.

$$PR = \frac{I(\mathbf{x})}{\frac{\sum CF}{years}} \quad (15)$$

Although $I(\mathbf{x})$ can be easily computed, the other variables need calculation. Therefore, CF can be computed through Equation 16, which indicates that the resulting PR is an updated variable, and $years$ depends on the characteristics of the project and the organization's viewpoint.

$$CF = \sum_{i=1}^{anos} \frac{CF_1}{1 + r^i} \quad (16)$$

III. Methodology

According to Sintra's Military Complex network' configuration and to the power losses considerations, both presented in II, this power network can be considered prone to losses due to:

- the billing of the reactive power' excedent;
- its operational voltage levels (MV and LV);
- the integration of some components, namely the transformers, that are near the end of their service life;
- its radial configuration;

In theory, the reduction of power losses, with the intent of increasing energy efficiency in Sintra's Military Complex MV-LV network, can be accomplished by the implementation of the four optimization strategies mentioned. Nonetheless, there are investment costs associated with these approaches that may not align with the PoAF budget protocols. Therefore, the investment costs need to grant efficient management of the PoAF budget to execute these strategies. Accordingly, there are two conflicting objectives: reduction of power losses and decrease in investment costs related to the optimization strategies. This problem can be formally established by considering a multiobjective optimization focused on providing a solution for implementation in Sintra's Military Complex power network.

However, the multiobjective optimization can culminate in a Pareto set of solutions instead of one single outcome. To obtain a single solution, it is necessary to engage in a decision-making process, where the decision-maker establishes certain criteria based on his/her perspective.

In agreement with the previous considerations, the adopted methodology for this investigation is based on the MP Approach (presented on [6]) and is composed of these six stages:

1) Formulation the multiobjective optimization problem;
2) Determination of power consumption scenarios;
3) Development of a computational tool for solving the multiobjective optimization problem;
4) Execution of the developed computational tool for each power consumption scenario to obtain the Pareto sets;
5) Development of a decision-making process;
6) Selection of the optimal solution based on the decision-making process.

The following section details each of the methodological steps mentioned above.

A. *The mathematical formulation of the multiobjective optimization problem*

Regarding its multiobjective quality, the optimization problem considers two objectives: $F(1)$ and $F(2)$, as computed in Equation 17. This problem intends to minimize both $F(1)$ and $F(2)$.

$$F = \min \{F(1), F(2)\} \quad (17)$$

The objective functions presented in Equation 17 can be computed through Equation 18, where the array $\mathbf{x}$ corresponds to the vector of the decision variables that are related to the four optimization strategies, as presented in Equation 19.

$$F = \begin{cases} F(1) = P(\mathbf{x}, Scen) = \sum S_{losses}^{i},\ i = 1, ..., n \\ F(2) = I(\mathbf{x}) = C(x_1) + C(x_2) + C(x_3) + C(x_4) \end{cases} \tag{18}$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} n_{cb} \\ Ppv \\ n_{taps} \\ n_{lines} \end{bmatrix} \tag{19}$$

The variable S_{losses}^{i} of Equation 18 refers to apparent power losses characterized in Equation 8, while $I(\mathbf{x})$ specifies the optimization strategies' investment costs. Each function $C(\mathbf{x})$ corresponds to the investment cost related to each strategy, by order of presentation. The description of the functions is based on previous projects completed by the PoAF and is presented in Equation 20.

$$C(\mathbf{x}) = \begin{cases} C(n_{cb}) = 10875 \cdot n_{cb} \\ C(Ppv) = 1.2 \cdot Ppv \\ C(n_{taps}) = 0 \cdot n_{taps} \\ C(n_{lines}) = 11210 \cdot n_{lines} \end{cases} \tag{20}$$

Each decision variable $\mathbf{x}$ corresponds to an optimization approach: n_{cb} is the number of capacitor banks to be replaced, related to the reactive power compensation; Ppv is the generating power of the DER to be installed; n_{taps} is the number of transformers' taps to be repositioned; n_{lines} is the number of lines to be installed in the power network.

Still, regarding Equation 18, it can be stated that $F(1)$ not only depends on the decision variables but also on the variable $Scen$. Due to the lack of real-time power consumption data, there is uncertainty regarding the definition of the load profiles. Hence power consumption scenarios must be set to represent the most important events in terms of power demand. As scenarios vary according to the fluctuations in the active and reactive power consumed at each bus, they only affect the calculation of $F(1)$ and do not imply $F(2)$.

Both objective functions impose restrictions on the optimization problem. These restrictions are:

- Restriction 1: compliance with power flow analysis method, resulting in its convergence;
- Restriction 2: limitation of voltage stability limits, considering $V^{min} = -15\%$ and $V^{max} = +10\%$ in Equation 5;
- Restriction 3: fulfilment of current stability limits, with $I_{ij}^{max} = 394$A in Equation 6 (related to the power cable datasheet);
- Restriction 4: guarantee of a decrease in $F(1)$, according to Equation 9;
- Restriction 5: set limits for $tan\phi$ related to the ellimination of the reactive power billing parcel, according to Equation 10;
- Restriction 6: compliance with maximum area ocuppied by the DER, characterized by Equation 12 with $A_{available} = 36400\text{m}^2$ (based on the available and suitable area);
- Restriction 7: limitation of the maximum DER installed power, according to Equation 11;
- Restriction 8: fulfilment of maximum PR defined by Equation 14 and with $t = 8$ years;

B. Definition of power consumption scenarios

The scarcity of available data regarding Sintra's Military Complex network's power consumption sets up uncertainty in terms of the characterization of this power distribution network. This problem can be solved by measuring the power consumption in a sampling period and analyzing the data to establish scenarios that portray this network's power consumption.

Therefore, in march 2021, several power meters were installed in TS 1, TS 2, TS 5, and TS 6 for this purpose. The collected data, in addition to the power distribution operator E-Redes information regarding the total consumption for the considered month, allowed for the definition of five distinctive scenarios. Scenarios 1, 2, 3, and 4 were selected based on the relationship between the active and reactive power consumption and the period of the day where they were registered (defined in [12]), while the Reference scenario is considered, as its designation suggests, the reference because it consists on the average of the power consumption values through the sampling period. A simple description of the scenarios and the associated apparent consumption power is presented in Table I, where Q_{ind} and Q_{cap} are the inductive and the capacitive reactive power, respectively.

TABLE I
DEFINITION OF THE SCENARIOS CONSIDERED FOR THE OPTIMIZATION

Scenario	Definition	S [kVA]
Reference	average S	204,74
Scenario 1	maximum P	358,56
Scenario 2	maximum Q_{ind}	151,17
Scenario 3	maximum Q_{cap}	166,47
Scenario 4	minimum P and Q_{ind}	115,73

C. Development of a computational tool for solving the multiobjective optimization problem

The computational tool used for solving the multiobjective optimization problem is based on NSGA-II due to its short execution time related to complex problems and its feasibility regarding the considered problem. The fundamental principles of this genetic algorithm are independent of the nature of the problem as it is described in [7] and [8]. Therefore, the only computational difference between two specific problems rests on the definition of the objective functions.

As presented before, the mathematical definition of the optimization problem' objective functions is introduced in Equation 19, but its computation needs to be developed according to the optimization strategies. Therefore, $F(1)$ and $F(2)$ must test the feasibility of the suggested values for the decision variables by confronting them with the problem's restrictions. Although NSGA-II does not integrate constraints on its original approach, these can take into account through the application of penalty functions, as explained in [9]. For this problem, the Death Penalty approach is the selected one. This approach can be described by Equation 21, where $p(\mathbf{x})$ is the penalty factor that take on a value close to $+\infty$ - in this case, the established value is 10^7.

$$F(\mathbf{x}) = \begin{cases} F(x), \text{ in case of compliance} \\ F(x) + p(\mathbf{x}), \text{ in case of violation} \end{cases} \tag{21}$$

Regarding $F(1)$ output, power losses can be computed by Equation 7 in a power flow analysis. In this case, the power flow function includes the evaluation of Restrictions 1 and 3. Nonetheless, Restriction 4 obliges the execution of the power flow twice: the first time for calculation of S_{losses}^{before} and the second time for computing S_{losses}^{after}, which implicates a test of that the decision variables according to the problem's remaining constraints in between. The performance of these evaluations takes place throughout three functions, each corresponding to n_{cb}, Ppv and n_{taps}, by order. In regard to the decision variable n_{lines}, it is assumed that Restriction 1 already evaluates the validity of the related optimization strategy.

The first function - related to n_{cb} - evaluates the reactive power compensation performed at each bus and compares it to the reference value of $tan\phi = 0.3$, according to Restriction 5. If there are violations, the power of the capacitor banks to be installed is calculated, according to the Schneider Electric catalog (in [13]).

Moreover, the function related to Ppv calculates the area to be occupied by the DER and applies Restriction 6. The computation of the area is based on previous PoAF projects where the empirical relation described by 13 can be considered.

Since n_{taps} represents an optimization strategy related to voltage control, the criteria used for determining the need for implementation of the related approach consists of the evaluation of the voltage in each bus according to Restriction 2. In case of violation, the taps' position' alteration is ranked based on the lowest difference between the voltage alternatives and 1 pu, and the n_{taps} lowest values are selected.

In the functions related to n_{cb} and n_{taps}, the assigned values of these variables may not correspond to the calculated modifications - for instance, if there is no need for altering the decision variables can still be indicating the implementation of such strategies. Hence in these functions, if there is a mismatch, the output of the objective function is automatically penalized. Therefore, a penalized output from $F(1)$ can be a result of this mismatch or a violation of Restrictions 1 to 6.

Regarding $F(2)$, the implementation of this function consists of the calculation of $I(\mathbf{x})$, the computation of PR, and evaluation of Restrictions 7 and 8. Concerning Restriction 7, a violation is not possible according to the TS where the connection to the DER is to be placed: currently, $P_{contractd} =$ 675 kVA, which is always superior to half of the maximum installed power because it cannot exceed the power of the connecting transformer (630 kVA). Restriction 8, however, can only be tested after calculating PR, which implies the computation of the cashflows CF; these values are computed based on the network's electricity bills. If this restriction's imposition is not verified, the result of $F(2)$ is penalized with the Death Penalty.

D. Decision-making process based on the MP Approach

The developed tool based on NSGA-II provides five sets of optimal results of equal validity, according to the five defined scenarios. However, not all solutions have the same importance from the decision-maker's perspective (the entity that decides the best solution). Through logical operations, it is possible to portray this entity's principles by taking on the MP Approach, as explained in detail in [6].

This decision-making process can vary depending on the decision criteria and the selected Aggregation Weighted Operator (OWA). For this optimization problem, the Laplace criterion is selected because it evaluates the solutions of each scenario, assuming that each one is of equal importance. The characteristic estimates, in the light of the Laplace criterion, can be calculated by Equation 22, where X_k is a solution to the optimization problem.

$$g^L(X_k) = min \frac{1}{Scen} \sum_{Scen=1}^{Scen_{total}} f(X_k, Scen) \tag{22}$$

Moreover, the development of the aggregated payoff matrix from the normalized payoff matrices (part of the MP Approach) involves the selection of an appropriate OWA, which Equation 23 defines. In this equation, one must consider that $k = 1, ..., K$, with k corresponding to a particular solution and K being the total number of solutions considered; and $i = 1, ..., q$, in which i is the number related to the optimization objective and q the total number of objective functions.

$$OWA(X_k) = \sum_{i=1}^{q} w_i \tag{23}$$

In 23, the variable w_i represents the weight attributed to each solution, based on the selected aggregation operator. The standard operators are the arithmetic average, maximum, and the minimum, to which correspond moderate, pessimistic, and optimistic decision-making perspectives; the difference between these operators is verified in Equations 24, 25 and 26, respectively.

$$w_i = \frac{1}{q}, i = 1, ..., q \tag{24}$$

$$w_i = \begin{cases} w_1 = 1 \\ w_i = 0, \ 1 = 1, ...q \end{cases} \tag{25}$$

$$w_i = \begin{cases} w_1 = 0 \\ w_i = 1, \ 1 = 1, ...q \end{cases} \tag{26}$$

The selection of the solution of the multiobjective optimization problem is accomplished by the application of Equation 27, with $k = 1, ..., K$ and $i = 1, ..., q$.

$$X_{sol}^{L} = max\, OWA \cdot \mu_p(X_k) \quad (27)$$

In the scope of this investigation, all operators are considered, which implies the generation of at least three optimal solutions, one for each considered OWA.

IV. Results

The results for each power consumption scenario were obtained by following the methodological stages, as is presented in Figure 2.

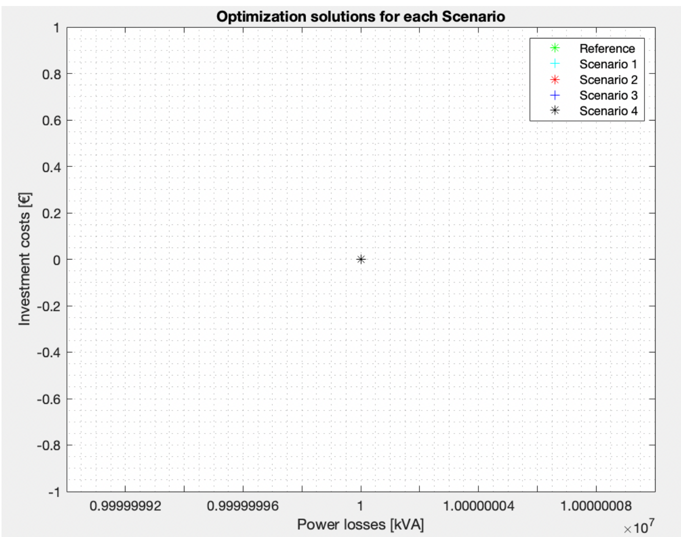

Fig. 2. Pareto sets for the established power consumption scenarios

The analysis of Figure 2 shows that the results for every simulation are identical, superposed, and not similar to Pareto sets, as expected. Every solution takes the same values for the objective functions: $F(1) = 10^7$ kVA and $F(2) = 0$ €. Considering that 10^7 is the penalty factor, it can be concluded that every $F(1)$ solution is penalized.

To better understand the successive penalization of these solutions, the current losses S_{losses}^{before} of Sintra's Military Complex power network can be analyzed. Thus these values and their comparison with each scenario's total consumption power are presented in Table II.

TABLE II
CURRENT POWER LOSSES IN SINTRA'S MILITARY COMPLEX NETWORK AND COMPARISON WITH THE TOTAL CONSUMPTION POWER, FOR EACH SCENARIO

	Current Losses [kVA]	**Percentage of current losses regarding total consumption power [%]**
Reference	7,496	3,662
Scenario 1	7,495	2,091
Scenario 2	7,498	4,961
Scenario 3	7,496	4,503
Scenario 4	7,498	6,479

Firstly, Table II highlights the short variation between the current losses for each scenario: the related standard deviation is $0,001$ KVA for an average of $7,497$ kVA; these values are in agreement with the Ref' current losses. Moreover, the standard deviation for the percentage of current power losses regarding the total consumption power is $1,449\%$ for an average of $4,503\%$. Although these values are in accordance with the Reference value, the proportion rate between power losses and consumption power is not as significant as expected. Furthermore, the reduction of the power losses shown in Table II depends on the implementation of the four optimization strategies considered in this investigation.

For the first considered optimization strategy - reactive power compensation - the results from Figure 2 imply that this measure does not apply to any scenario. Additional simulations demonstrate that the capacitor banks' replacement for Scenarios 2, 3, and 4 are viable, considering the following recommended installations:

- a $38,7$ kVA capacitor bank in TS 4, for Scenario 2;
- a 175 kVA capacitor bank in TS 5, a $38,7$ kVA capacitor bank in TS 8 and a $68,7$ kVA capacitor bank in TS 9, for Scenario 3;
- the installation of a 250 kVA capacitor bank in TS 1, a 150 kVA capacitor bank in TS 3 and a $38,7$ kVA capacitor bank in TS 5, for Scenario 4;

However, when applying these modifications to the power network, an increase in power losses was verified, as can be analyzed in Table III.

TABLE III
COMPARISON BETWEEN THE CURRENT LOSSES AND THE LOSSES AFTER THE REPLACEMENT OF THE SUGGESTED CAPACITOR BANKS

	Current Losses [kVA]	**Losses after the optimization for nbc [kVA]**
Reference	7,496	7,496
Scenario 1	7,495	7,495
Scenario 2	7,498	7,501
Scenario 3	7,496	7,557
Scenario 4	7,498	7,522

Therefore, the results presented in Table III involve the violation of Restriction 4 and hence the penalization of $F(1)$. Additionally, the implementation of this optimization measure is proven inadequate for the Sintra's Military Complex power network despite the theoretical principles that indicate otherwise.

Furthermore, the implementation of the optimization strategy described by Ppv also proves itself inadequate. Table IV intends to portray an example of the impact of DER installation of 10 kW on power losses.

Although this measure is theoretically beneficial to power losses' improvement in distribution networks and the limits imposed on this variable do not violate the associated restrictions (Restrictions 6 and 7), its implementation caused an increase in power losses for every scenario, as the example of Table IV demonstrates. Consequently, these results imply

TABLE IV
COMPARISON BETWEEN THE CURRENT LOSSES AND THE LOSSES AFTER THE IMPLEMENTATION OF A 10 KW DER

	Current Losses [kVA]	Losses after the installation of a 10 kW DER [kVA]
Reference	7,496	7,533
Scenario 1	7,495	7,534
Scenario 2	7,498	7,532
Scenario 3	7,496	7,531
Scenario 4	7,498	7,532

a violation of Restriction 4, which penalizes $F(1)$. Despite some theoretical advantages, this inadequacy is in accordance with the fact that power losses reduction is better performed for ring networks, based on their acceptable penetration levels, as opposed to radial networks.

Regarding the voltage control measure of transformer's taps adjustment, this strategy also proves itself inadequate in meeting the objectives and restrictions of the problem. Considering that this strategy is only applied if the voltage at each bus is not within the limitations imposed by Restriction 2, these values were assessed for every scenario, as analyzed in Table V.

The modulus of the voltage shown in Table V demonstrates that there is no violation in terms of Restriction 2, which indicates that there is no necessity to implement this optimization strategy for this power network for any scenario.

Additionally, the topological reconfiguration also proved to be inextensible to the problem's objectives. Although the ring configuration is, in theory, less prone to power losses, the installation of a power line connecting TS 4 and TS 9 increases power line length. As power line length and power losses are proportional, the benefits associated with the ring configuration do not surpass the increase in power losses caused by the possible installation of the power line. Additional simulations exposed the increase in power losses caused by the installation of this power line. These results present themselves in Table VI.

Therefore, the increase in S_{losses}^{after} implies the violation of Restriction 4 and thus the application of a penalty to $F(1)$.

The inadequacy of the proposed optimization strategies is proved through its individual analysis. Although the optimization problem takes into account the combination of every decision variable simultaneously, the individual unfeasibility of each measure reinforces the joint impracticability of all of

TABLE V
VOLTAGE MODULUS FOR EACH BUS OF SINTRA'S MILITARY COMPLEX POWER NETWORK, FOR EACH SCENARIO

	Voltage modulus for each bus				
Bus	**Reference**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
TS1 - MV	1	1	1	1	1
TS1 - LV	1,0002	1,0002	1,0002	1,0002	1,0002
TS2 - MV	0,9998	0,9998	0,9999	0,9998	0,9999
TS2 - LV	0,9998	0,9998	0,9999	0,9998	0,9999
TS3 - MV	0,9996	0,9996	0,9997	0,9996	0,9997
TS3 - LV	0,9995	0,9995	0,9997	0,9996	0,9997
TS4 - MV	0,9995	0,9995	0,9997	0,9996	0,9997
TS4 - LV	0,9995	0,9995	0,9997	0,9996	0,9997
TS5 - MV	0,9985	0,9984	0,9986	0,9985	0,9986
TS5 - LV	0,9984	0,9983	0,9986	0,9985	0,9986
TS6 - MV	0,9973	0,9971	0,9975	0,9973	0,9975
TS6 - LV	0,9973	0,9972	0,9976	0,9973	0,9976
TS7 - MV	0,9967	0,9965	0,9969	0,9967	0,9970
TS7 - LV	0,9967	0,9965	0,9969	0,9967	0,9970
TS8 - MV	0,9963	0,9961	0,9966	0,9964	0,9966
TS8 - LV	0,9962	0,9961	0,9965	0,9963	0,9966
TS9 - MV	0,9958	0,9956	0,9961	0,9959	0,9961
TS9 - LV	0,9957	0,9955	0,9960	0,9957	0,9960

TABLE VI
COMPARISON BETWEEN THE CURRENT POWER LOSSES AND THE LOSSES AFTER THE IMPLEMENTATION OF THE SUGGESTED POWER LINE BETWEEN TS 4 AND TS 9

	Current Losses [kVA]	Losses after the installation of a power line between TS4 and TS9 [kVA]
Reference	7,496	7,508
Scenario 1	7,495	7,507
Scenario 2	7,498	7,510
Scenario 3	7,496	7,508
Scenario 4	7,498	7,510

them. Therefore, the results of the developed computational tool' execution demonstrate that there is no combination of the implementation of the considered optimization measures that cause a decrease in power losses for Sintra's Military Complex.

Moreover, the proposed optimization measures are associated with investment costs $F(2)$, which is also an optimization objective. As it can be analysed in Figure 2, every solution for every scenario has a null cost, which is only possible if n_{cb}, Ppv and n_{lines} are also null (n_{taps} does not affect the computation of $F(2)$).

The fact that every solution presents the same output, as shown in Figure 2, can be explained by the operation of the adopted genetic algorithm. The optimization program suggests random values (at first) for each decision variable. The feasibility of these variables regarding the problem's objectives is assessed for each objective by the imposed restrictions. In consequence, a violation of these constraints implies the application of a penalty factor. Moreover, the reproduction, recombination, and mutation processes choose the individuals that pass on to the next generations based on the non-dominated sort and the crowding distance criteria. As demonstrated before, the absence of strategies' implementation is preferable in terms of meeting the objective set for $F(1)$, which justifies the tendency of the individuals that integrate the newest generations to associate with decreasing values for the decision variables. Therefore, the decision variables converge to 0 to meet the objectives. However, the absence of measures still penalizes $F(1)$ due to the imposed reduction of power losses by Restriction 4, which explains the results of $F(1)$ presented in Figure 2. Additionally, the decision variables' convergence to 0 is also in agreement with the results of $F(2)$ for every scenario.

The obtained solutions for this stage exclude the performance of the last methodological step, which is the application of the decision-making process.

The applied methodology involves the definition of various parameters of the problem. Some optimization problem's particularities are based on principles of the literature revision or similar projects, but alternatives could also be equally eligible. Therefore, the preeminent identified limitations are:

- The disregard for traditional power loss mitigation measures at the expense of adopting network management strategies;
- The consideration of local reactive power compensation in opposition with global compensation actions;
- The limitation of the topological reconfiguration strategy to the installation of a power line between TS 4 and TS 9;
- The limitation of the DER installation strategy in terms of its location and connection;
- The randomness of the adopted computational tool;
- The difficulty in computing the implementation of n_{cb} and n_{taps}.

V. Conclusions

This investigation proposes a study on how to increase energy efficiency in Sintra's Military Complex distribution network. Through literature revision, power losses were identified as an indicator of energy efficiency, and four mitigation strategies were proposed, which are: reactive power compensation, installation of a DER, adjustment of transformer taps, and topological reconfiguration. These strategies' implementation is associated with its economic aspects, which must also be considered and minimized.

The chosen methodology for accomplishing the objective is adapted from the multiobjective decision-making process based on the MP Approach. This method consists of six stages: formulation of the optimization problem, the definition of the consumption scenarios, development of the computational tool to solve the problem, execution of the program to obtain the optimization results, application of the decision-making process, and selection of the final solution.

The obtained results show that the considered optimization strategies do not cause a reduction in power losses in Sintra's Military Complex distribution network for any scenario. Therefore, its implementation is unadvised in terms of increasing energy efficiency in this network.

In the future, some investigations based on the developed work could be pertinent, such as:

- The study of the applicability of traditional strategies in terms of power losses mitigation for the considered power network;
- The investigation of the adequacy of the current reactive power compensation in Sintra's Military Complex, considering other solutions;
- The test of the applicability of the developed methodology and objectives to other distribution networks;
- The investigation of the feasibility of the considered strategies in terms of grid' reliability, taking into account the associated decrease in energy efficiency.

References

[1] José Pedro Sucena Paiva (2005). Redes de Energia Elétrica. Uma Análise Sistémica. IST Press.

[2] Murray G. Patterson (1996). What is energy efficiency?: Concepts, indicators and methodological issues. Energy Policy, 24(5), 377-390.

[3] Rune Gustavsson, Leif Marcusson (1996). Increasing Energy Efficiency by Reducing Losses and Promoting Value Propositions. Energy Efficiency Improvements in Smart Grid Components, 24(5), 377-390.

[4] Tractebel Engineering and Ecofys. (2015). Identifying Energy Efficiency improvements and saving potential in energy networks.

[5] Jorge Pereira, Jorge Alves, Manuel Matos (2014). Investigação operacional em ação: casos de aplicação. In Investigação Operacional em Ação: Casos Práticos (pp. 589-608). Imprensa da Universidade de Coimbra.

[6] Joel Gomes Pereira Júnior (2014). Modelos e Métodos de Tomada de Decisões Multiobjetivo em Ambiente com Incertezas e Suas Aplicações. (Doctoral dissertation, Universidade Federal de Minas Gerais).

[7] Kalyanmooy Deb, Amrit Pratap, Sameer Agarwal, T. Meyarivan (2002). A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 2, 182-197.

[8] Abdullah Konak, David W. Coit, NAlice E. Smith (2006). Multi-objective optimization using genetic algorithms: A tutorial. Reliability Engineering and System Safety, 91, 992-1007.

[9] Özgür Yeniay, Beytepe, A. (2005). Penalty Function Methods for Constrained Optimization with Genetic Algorithms. Mathematical and Computational Applications, 10(1), 45-56.
[10] Krishneel Prakash, F. R. Islam, Avneel Lallu, Kabir Al Mamum (2016). Review of Power Systems Distribution Network Architecture. In 2016 3rd Asia-Pacific world Congress on Computer Sciencean Engineering (APWC on CSE) (pp. 124-130). Schneider Electric.
[11] EDP Distribuição. (outubro de 2018). Manual de Ligações à rede elétrica de serviço público. Portugal.
[12] ERSE. (december of 2021). Estrutura Tarifária do Setor Elétrico em 2021.
[13] Schneider Electric (2020). Power Factor Correction. Power Quality. Catalogue 2020. Low Voltage Power Factor Correction Components.
[14] Víctor H. Méndez Quezada, Juan Rivier Abbad, Tomás Gómez San Román (2006). Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation. IEEE Transactions on Power Systems, 21(2), 533-540.
[15] Mohammad A. Alrumaih, Abdullah M. Al-Shaalan (2019). Impact of PV Distributed Generation on Loop Distribution Network. Journal of Power and Energy Engineering, 7(8), 27-42.