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Multistage Planning Model with Photovoltaic Distributed Generation in Low Voltage Networks of Rural Electrical Systems

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Abstract. In an emerging electricity market in which concepts of energy transition, energy security, quality and efficiency are included, it is essential to incorporate renewable energies as a fundamental factor for the development and sustainability of electricity systems. The evolution of demand requires the electrical system to guarantee quality and efficiency, in this aspect planning is fundamental, therefore, the current research proposes a multistage planning model with photovoltaic distributed generation in low voltage networks of rural electrical systems for cost optimization. In the first stage, this model uses clustering optimization methods, approximate analysis methods of the low voltage network, simultaneity factors by demand blocks, and 10x10x4x3 factorial experimental design, which allow the location and capacity of distributed generation to be able to be established. In addition, the trend and econometric methods determined that the annual demand growth rate is 4.99%. For the technical assessment were established two alternatives, on the one hand with distributed generation and, on the other hand without this one, In the first case, the outcomes of the load flows with sum of currents methods, the monthly energy lost is 59,517 kWh, 149,898 kWh and 285,278 kWh for the years 2027, 2033 and 2043, respectively as well as the reduction of voltage drops in average percentage is 0.68%, 0.88% and 1.06% for the years 2027, 2033 and 2044, respectively. Finally, the minimum cost with distributed generation is US$ 134,120.47, NPV of 678,519.07, and IRR of 50.86%.

Keywords. Photovoltaic distributed generation, electrical system planning, rural electrical systems.

1. Introduction

In Peru, it is known there is no a suitable attention to the development of rural areas. Besides, in many cases, they are not considered in an energy planning process that is inclusive, coherent, understandable, transparent and systemic which can facilitate better access to renewable energy and, take into the aspects of its local and regional environment account. The lack of decision to establish regulations in an inclusive planning, added to the technical conditions of operation, maintenance, geographical conditions and demand, make the development of electrical systems in rural areas difficult. According to statistical reports [1] about the quality of voltage and quality in

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rural systems, of the total of 15 companies, on average 17.93% present voltage levels that exceed the tolerances established in the NTCSER, likewise, the amount compensation for a poor voltage quality at the national level amounts to US$ 1,349,286. In particular, energy requirements have not been dealt with in a proper way which justifies the importance of identifying a coherent, understandable, transparent and systemic energy planning process making it easier to get a modern energy based on resident requirements and local environmental conditions [2]. Consistent with what is indicated, in Peru, the lack of decision to establish regulations that allow a comprehensive and timely planning, added to the geographical and demand conditions then this make it difficult the development of electrical systems in rural areas. Rural Electrical Systems have evolved with improvements in efficiency in recent years, despite this, the voltage levels, number and duration of interruptions exceed the tolerances established in the NTCSE, the lack of incorporation of renewable energies in these systems, besides due to the inability to conduct planning in distribution companies, a multistage planning model for distribution systems is proposed that incorporates Photovoltaic Distributed Generation in the Low Voltage Networks of Rural Electrical Systems and allows us to improve quality and efficiency indicators. and that guarantees the continuity of the electrical energy service, so regarding to planning with distributed generation, [3] it was developed a methodology for the massification of photovoltaic distributed generation in low voltage networks, evaluating the impact on voltage profiles, losses and conductor chargeability, in the case of [4] it was developed the planning of electrical distribution networks with distributed generation, another aspect that must be taken into account is the impact of distributed generation on the distribution system [5], it is also important to evaluate the viability and coverage of implement photovoltaic distributed generation and how it is done [6], in all this it is important to develop proposals for regulatory guidelines for photovoltaic distributed generation as it is suggested [7]. Other technical aspects to take into account, [8] which highlights the location points of the distributed generation, duly weighted according to their load magnitude in order to determine the probability distribution of best fit, in that same line [9] it proposes an algorithm based on a set of criteria to evaluate different distributed generation options in rural Bhutan, [10]which developed a mixed integer nonlinear programming model in the search for multistage planning to optimize costs, [11], it performs a quasi-analysis. dynamic of a local distribution system with distributed generation modifying the 13-node IEEE system, [12],it uses a multi-objective search algorithm evaluating the capacity of the existing system and performs the demand projection for the next 10 years, [13] that presents distribution expansion planning model with multi-stage distributed generation, [14], that uses a stochastic multi-objective optimization model for the planning of hybrid AC-DC intelligent distribution systems, [15] it develops a two-level planning model of the distribution system with an economic risk-based approach, [16]it presents a comprehensive long-term distribution planning framework from the perspective of local distribution companies and , [17]analyzes the release of network capacity and calculation of incremental addition of distributed generation for planning the distribution system, finally [18], [19], [20], [21],it is proposed various subsidy models for the incorporation of renewable energies, mainly photovoltaic, it is important when a new technology is incorporated into the system.

2. Investigation Development

The general multistage planning model for the incorporation of photovoltaic distributed generation in low voltage networks of rural electrical systems includes the stages indicated in figure 1, six stages are established.

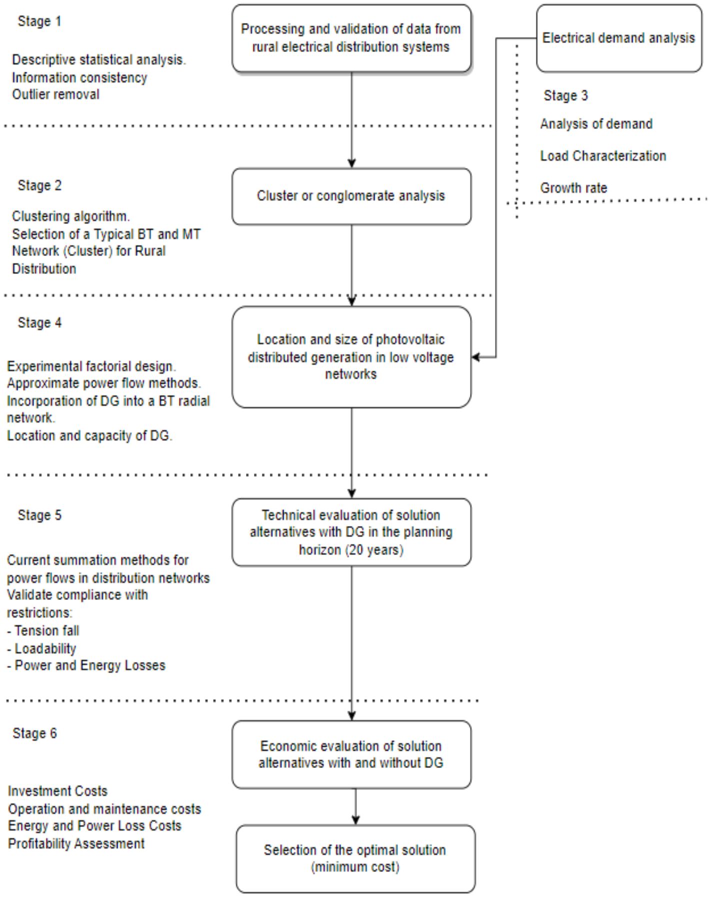

Figure 1. General multistage planning model for the incorporation of photovoltaic distributed generation in low voltage networks of rural electrical systems.

2.1. Stage 1: Processing and Validation of Data from Rural Electrical Distribution Systems

Data processing and validation matches performing a statistical analysis of the technical information of the electrical systems data, identifying atypical values, atypical data or not normal observations (figure 2). One of the ways of analyzing data is multivariate analysis, in a broad sense, it refers to all statistical methods that simultaneously analyze multiple measurements of each individual or object under investigation

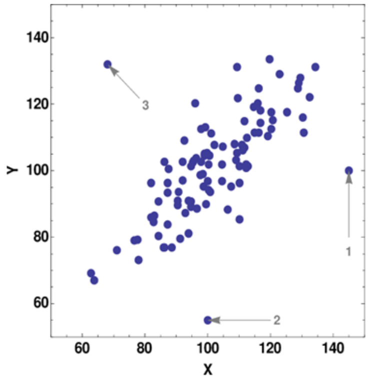

Figure 2. Examples of various outliers found in regression analysis. Case 1 is an outlier with respect to X. Case 2 is an outlier with respect to Y. Case 3 is an outlier with respect to X and Y.

2.2. Stage 2: Cluster or Conglomerate Analysis

Clustering analysis is widely used in information classification; it is assumed that the examples in the training set are naturally grouped into basically subsets [22].

K-means, it is an iterative method that initially creates K clusters and reconsiders the assignment of examples to the K clusters in each iteration until convergence is reached (when no examples change clusters). Specifically, it is designed to work with continuous descriptive variables and uses the squared euclidean distance to calculate the dissimilarity between elements [22].

It is based on the idea that, given a set of mean vectors, $\{\bar{x}_1, \dots, \bar{x}_K\}$, the intracluster dispersion can be expressed as follows:

$$I(C) = \sum_{k=1}^{K} N_k \cdot \sum_{x_i:C(x_i)=k} \|x_i - \bar{x}_k\|^2 \quad (1)$$

In the previous formula, x¯_k it it is the mean vector (center) associated with the kth cluster and N_k it is the number of examples assigned to that cluster. Thus, the optimization objective can be reinterpreted as assigning the examples of the training set to the K clusters, in such a way that the average dissimilarity of the examples with respect to the center of their respective clusters is minimized. In that sense, the objective can be expressed as follows:

$$\underset{C;\{\bar{x}_1,\dots,\bar{x}_k\}}{argmin} \sum_{k=1}^{K} N_k \cdot \sum_{x_i:C(x_i)=k} \|x_i - \bar{x}_k\|^2 \quad (2)$$

Note that there are two parameters obtained from this optimization process: the assignment function, C, and the final set of centers $\{\bar{x}_1, \dots, \bar{x}_k\}$.

Figure 3 shows three dendrograms constructed using the three measurements presented on a simple example data set:

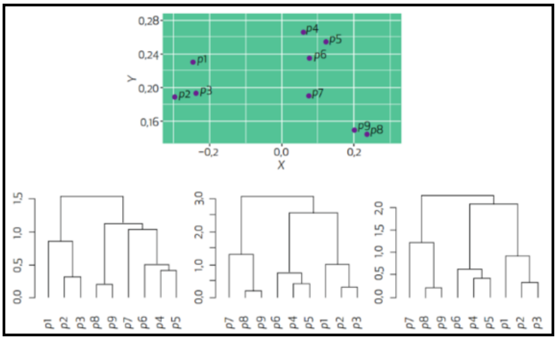

Figure 3. Test data set and dendrograms obtained with agglomerative clustering of minimum dissimilarity (left), maximum dissimilarity (center), and average dissimilarity (right).

2.3. Stage 3: Analysis of Electrical Demand

The econometric model tries to express the mathematical relationship between the variable explained by the model and the variables that could explain its behavior. If the model has only one equation, it is called a "single-equation model"; while if the model considers more than one equation, it is known as a "multiple-equation model". A multi-variable model could take the form:

$$Y = \lambda_1 + \lambda_2 X_1 + \ldots + \lambda_n X_{n-1} + u \tag{3}$$

From equation (Y), which is known as the dependent variable (endogenous), it is the variable whose behavior is important to be predicted; and those which are located on the right side of the equation (X1,... Xi,.... Xn-1), they are known as "explanatory" or "independent" variables then, they are those that are considered to influence the behavior of the dependent variable. The terms λ are the model parameters obtained from historical information and, the term "u" represents the stochastic error (disturbance term) which is typical to the model.

2.4. Stage 4: Location and Size of Distributed Photovoltaic Generation in Low Voltage Network

Approximate Methods with Uniformly Distributed Loads. When loads are uniformly distributed, it is not necessary to model each load to determine the total voltage drop from the source end to the last load. Figure 4 shows a generalized line with ''n'' uniformly distributed loads [23].

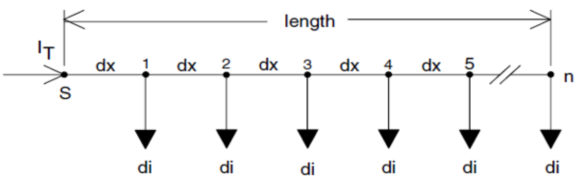

Figure 4. Uniformly distributed loads.

Equation 4 gives the general equation for calculating the total voltage drop from the source to the last node ''n'' for a line of length l.

$$Vdrop_{total} = Re\left\{\frac{1}{2} \cdot Z \cdot I_T\right\} \tag{4}$$

The equation to calculate the total three-phase power loss in the line is given by:

$$P_{loss_{total}} = 3 \cdot \left[\frac{1}{3} \cdot R \cdot |I_T|^2\right] \tag{5}$$

Factorial designs manipulate two or more independent variables and include two or more levels of presence in each of the independent variables [24].

In general, it is said that a factorial design composed of factor A with n_1 levels, factor B with n_2,… factor K with nk levels, will have:

n1 x n2 x…x nk experimental runs

The full factorial design is the general way to compose any design where different levels are used. Full factorial designs are unusual, as they are difficult to analyze and interpret [25].

2.5. Stage 5: Technical Evaluation of the DG Solution Alternatives in the Planning Horizon

It consists in calculating the currents in the loads from the initial voltages and the power of the loads, and then adding these branches to obtain the upstream currents up to the busbar of origin of the distribution system. Then we start from the origin to calculate the voltage drops in the downstream branches and their respective voltages. This process is followed iteratively until convergence is found in the voltages at the nodes or bars of the system.

The known variables are the source"volt'ge (Vs = 1.0) and the loads (Pi+jQi), the variables to be calculated are the currents (Ii) and the voltages (Vi) in the load nodes or bars.

In each of the nodes, tensions equivalent to or very close to 1.0 in p.u are initially assumed. The currents in sections 1 and 2 are calculated:

$$\hat{I}_{2(k)} = \left(\frac{\hat{S}_2}{\hat{V}_{2(k)}}\right)^* \tag{6}$$

$$\hat{I}_{1(k)} = \left(\frac{\hat{S}_1}{\hat{V}_{1(k)}}\right)^* + \hat{I}_{2(k)} \tag{7}$$

The voltages of downstream nodes are calculated:

$$\hat{V}_{1(k+1)} = \hat{V}_s - \hat{Z}_1 \cdot \hat{I}_{1(k)} \tag{8}$$

$$\hat{V}_{2(k+1)} = \hat{V}_{1(k+1)} - \hat{Z}_2 \cdot \hat{I}_{2(k)} \tag{9}$$

The node voltages of the current iteration are compared against the values of the previous iteration. If it is fulfilled $\left|V_{i(k+1)} - V_{i(k)}\right| \leq \varepsilon$, the load flow calculation is completed and the values obtained in the last iteration are reported.

If the previous inequality is not met, the voltage difference is added to each of the nodes and the next iteration continues.

ε : It is the acceptable error tolerance for the system equations to converge (example 0.001).

V_S : Module of the known voltage at the source (specified value).

$V_{S(k+1)}$: Module of the voltage calculated in the "k+1" iteration at the source node.

$V_{1(k+1)}, V_{2(k+1)}$: Module of the tensions calculated in nodes 1 and 2, iteration "k+1".

$\hat{I}_{1(k)}, \hat{I}_{2(k)}$: Currents in sections 1 and 2 corresponding to iteration "k".

$P_{c1}, Q_{c1}, P_{c2}, Q_{c2}$: Active and reactive power of the loads in nodes 1 and 2.

$\hat{Z}_1, \hat{Z}_2$: Impedances of sections 1 and 2.

The described power flow procedures for radial systems are followed for the three phases and neutral (R, S, T and N) one by one, in order to represent their unbalanced characteristic.

2.6. Stage 6: Economic Evaluation of the Solution Alternatives with GD Selection of the Optimal Solution

The objective function for the basic distribution system planning model taken, which will be used to evaluate the electrical costs and losses of a given configuration, as well as the voltage and power flow levels to verify the correct operation of the topology to be studied.

$$OF = \sum_{t=1}^{nS} \beta^{(t-1)nT} (C_t^1 + C_t^2 + C_t^4 + C_t^5 + C_t^6) \tag{10}$$

Donde:
nS: Number of stages.
$\beta^{(t-1)nT}$: Exchange rate.
C_T^1: Cost of a new circuit and its enhancement.
C_T^2: Cost of a new substation and its repowering.
C_T^3: Cost of a protection element.
C_T^4: Operation and Maintenance Cost.
C_T^5: Cost of a Photovoltaic DG.
C_T^6: Operating costs due to energy losses.

This optimization model has the following restrictions:

$$S_{S_{i,l,t}} = S_{D_{i,l,t}} - S_{G_{i,l,t}}$$

$$\left|\frac{V_{i,l,t-}V_{j,l,t}}{Z_{i,j,f,t}}\right| \leq I_{i,j}^{max} \tag{11}$$

$$S_{S_{i,l,t}} \leq S_{Ss}^{max}$$

$$S_{G_{i,l,t}} \leq S_{Gg}^{max}$$

$$V_i^{min} \leq V_{i,l,t} \leq V_i^{max}$$

Where:
$S_{Si,l,t}$: Power injected per substation in node i
$S_{Gi,l,t}$: Power injected by DG in node i
$S_{Gi,l,t}$: Power demanded at node i
$V_{i,l,t}$ y $V_{j,l,t}$: Voltage at nodes i and j respectively
$Z_{i,j,f,t}$: Feeder impedance between nodes i and j
S_{Ss}^{max} : Maximum capacity of substation S
G_{Gg}^{max} : Maximum GD capacity
V_i^{min} y V_i^{max}: Maximum and minimum voltage in i respectively.

3. Discussion and Analysis of Results

It is important to highlight the results achieved in the present research, the proposed model with the incorporation of photovoltaic distributed generation in terms of investment costs is minimal, in terms of economic profitability is viable, also in technical terms it contributes to improve the performance of energy losses and voltage drop.

The fulfillment of the general and specific objectives is a consequence of the results of the application of the model in a real low voltage network, the analysis of clusters by means of optimization methods allows the grouping in two significant groups of distribution substations considering the characteristics of the installations, The result of this stage is the selection of the feeder A4270 of the Union SET, the cluster analysis shows several advantages and benefits in the application in the electrical distribution systems [26], 02 clusters were determined (figure 5), also, the clustering helps to design medium and low voltage networks [27].

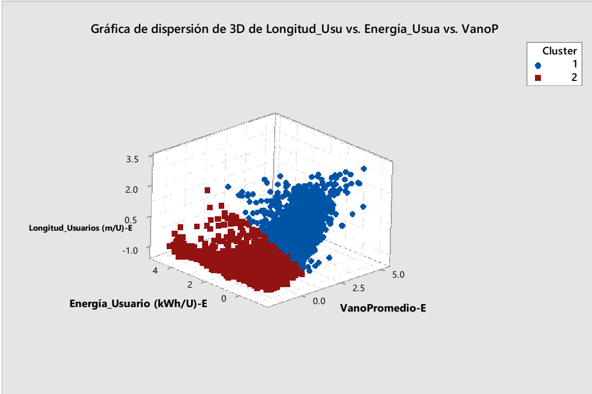

Figure 5. Cluster quantity considering length per user, energy consumption per user and average span.

The study of the electricity market has two fundamental objectives, the determination of the growth rate and the characterization of demand, for the first case, trend and econometric methods were used with a result of 4.998% anual (table 1) growth and in the second case, the Low, Medium and Peak demand blocks with simultaneity factors of 0.25, 0.43 and 0.83 respectively (figure 6), trend and econometric methods are widely used in demand studies in planning of main and secondary transmission systems, as well as in regulatory processes such as Distribution Added Value, demand forecasting is an important input for the expansion of electrical power systems and a determining factor for decision making in the electricity market [28].

Table 1. Growth rates of the electrocentro ser dealership arealong caption.

Year	Growth rate %
2023	10.61%
2033	4.16%
2042	4.16%
Average rate (%)	4.998%

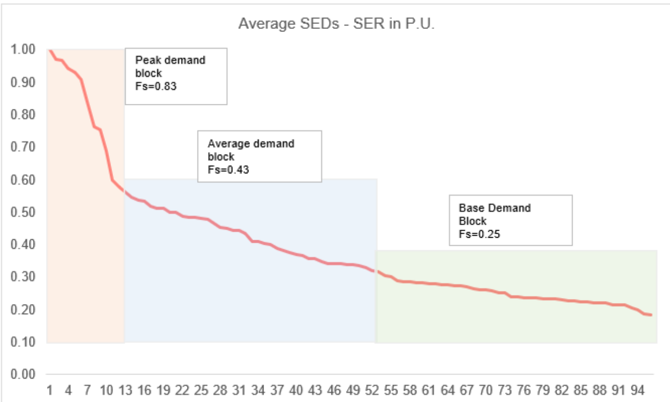

Figure 6. Diagram of load duration and demand blocks.

The 10x10x4x3 experimental factorial design, figure 7 shows the main effects on power losses, the use of approximate methods and simulation using power flows allowed us to establish that the distributed generation must be located 60% of the Distribution Substation and the capacity of the distributed generation must be similar to the block of medium demand (figure 8), since the proposal in this research is not to have storage elements. In relation to considering block schedules and the location of the load at specific points, they agree with the criteria established by [8], which establishes a probabilistic methodology for the selection and location of distributed generation. On the other hand, [16] considers in the planning the incorporation of controlled and uncontrolled vehicular electric load, this type of loads associated with distributed generation could be analyzed in typical sectors 1 and 2 where there is a greater concentration of load. An important aspect that they mention [17] is that, in addition to optimal positioning and size, it depends on its ability to produce energy at the appropriate times and levels.

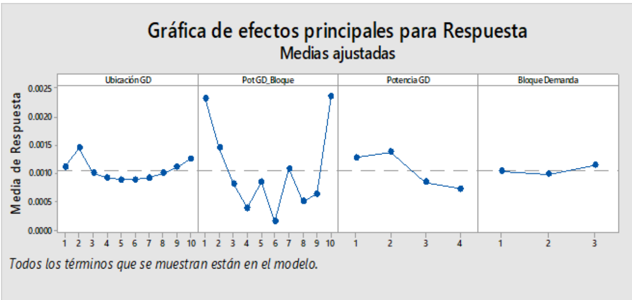

Figure 7. Main effects of the response.

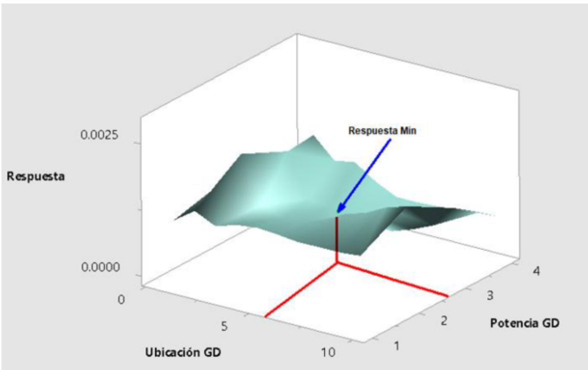

Figure 8. Surface plot DG location, DG power and response.

The outcomes of the technical evaluation are relevant in this research, because two solution alternatives are established with and without photovoltaic distributed generation, after the evaluation of the diagnosis that allows to know the current operating conditions of the system through load flows, considering the restrictions of voltage drops +- 7. Likewise, the available solar energy was evaluated in Wh/m2 where the least unfavorable hours are from 7 am to 4 pm, in contrast to the demand blocks, the participation of distributed photovoltaic generation is 7.5 hours in the medium demand block and 4.5

hours in the base demand block, figure 10. The results of the simulations using load flows show favorable values with the incorporation of PV distributed generation, the monthly energy which is not lost in kWh is 59,517 kWh, 149,898 kWh and 285,278 kWh for the years 2027, 2033 and 2043 respectively, also, the reduction of voltage drops in average percentage is 0.68%, 0.88% and 1.06% for the years 2027, 2033 and 2044 respectively. The results of [11], [3], [4], [5], [6] and [12] agree with the results of the research in finding impacts on voltage levels and losses by incorporating distributed generation, in the last case also considering the future growth of demand and the location of distributed generation. Contrary to the research approach, [15] and [13] propose the incorporation of batteries in the planning with distributed generation and propose flexibility policies in the economic issue, because the incorporation of batteries increases the investment costs, in the second case.

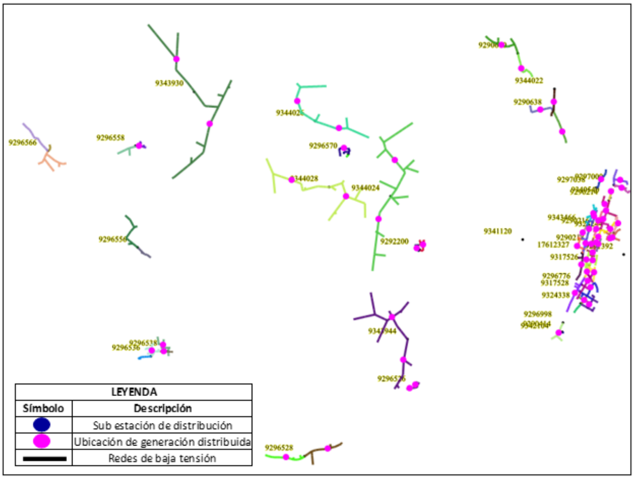

Figure 9. Map of the Generation distributed in BT of the A4270.

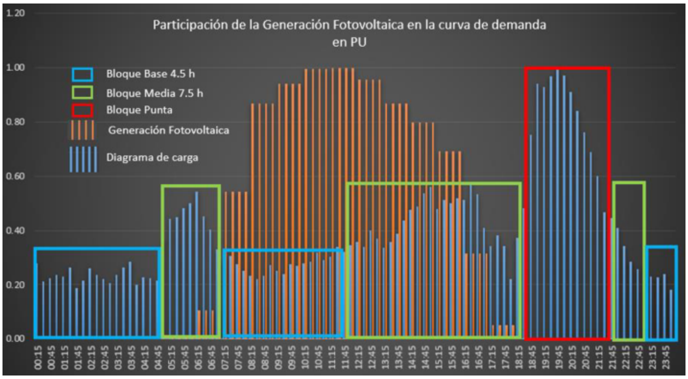

Figure 10. Participation of photovoltaic generation in the demand curve in PU.

It is worth mentioning the limitations at the time of collecting the information, as well as the quality and consistency of the technical and commercial information of the distribution companies at the national level.

The objective function of planning is to minimize costs considering solution alternatives, technical and regulatory restrictions. Thus, after analyzing the technical aspects, the best option is alternative 1, which considers photovoltaic distributed generation as part of the solution with investment costs of US$ 134,120.47, NPV of 678,519.07 and IRR of 50.86%, which indicate that alternative 1 is economically profitable and viable. The results obtained are consistent with those obtained by [10] and [9], who obtain lower costs with the incorporation of distributed generators, among other elements, compared to other alternatives. As any new technology is subject to economic incentives, [18], [19], [20] and [21] propose different subsidy models for the incorporation of photovoltaic distributed generation.

According to the research reviewed, the proposed model is novel and generates better results, because it allows a detailed analysis of each stage from data analysis, market analysis, technical evaluation and economic evaluation, the latter is essential for making decisions on the feasibility of the projects, Likewise, the model includes cluster analysis and experimental factorial design. No research was found that proposes planning models with the incorporation of distributed photovoltaic generation in low voltage grids in rural sectors; the application of other research is carried out on ideal grids and the results could not be reliable at the time of implementation in real grids.

Future work from this research is to analyze the effect of the incorporation of low voltage distributed generation in medium voltage and transmission levels, as well as to analyze the reliability of the system in terms of minimizing the expected energy not supplied [14].

4. Conclusions

In this research work, a planning model for electrical distribution systems was developed with the incorporation of Photovoltaic Distributed Generation in the Low Voltage Networks of Rural Electrical Systems. This model has 06 stages that, applied to a real low voltage network of the SET Union Feeder A4207 allowed to fulfill the objective function of minimizing costs, favorable economic indicators, improving the performance of energy losses and voltage drop.

Thus, in the first stage of the model, the analysis of clusters was carried out by means of clusteting optimization methods, resulting in two significant groups of distribution substations with similar characteristics, the result of this stage is the choice of the Feeder A4270 of the Union SET.

Likewise, in the next stage, the market analysis was carried out where a 4.99% annual growth rate was determined to project the demand by means of econometric and trend models, also the load characterization allowed establishing the Low, Medium and Peak demand blocks with simultaneity factors of 0.25, 0.43 and 0.83.

It should be noted that the optimal location and capacity of the Photovoltaic Distributed Generation in the Low Voltage Networks of the Distribution Substations were established by means of the 10x10x4x3 experimental factorial design, the use of approximate methods and the simulation through power flows, it was determined that the distributed generation should be located at 60% of the Distribution Substation and the capacity of the distributed generation should be similar to the medium demand block, since the proposal in this research is not to have storage elements.

The results of the technical evaluation are relevant, since it was determined to what extent energy losses are reduced with the incorporation of Photovoltaic Distributed

Generation in the Low Voltage Grid, two alternative solutions were established with and without photovoltaic distributed generation, after the evaluation of the diagnosis of the current operating conditions of the system through load flows, considering the technical restrictions, taking into account the available solar energy in Wh/m2 of less unfavorable hours from 07h00 to 16h00, in contrast to the demand blocks and the participation of photovoltaic distributed generation, the monthly energy that is not lost in kWh is 59,517 kWh, 149,898 kWh and 285,278 kWh for the years 2027, 2033 and 2043.

Thus, in contrast with the criteria established in the previous conclusion, the extent to which the voltage drop improves with the incorporation of Photovoltaic Distributed Generation in the Low Voltage Grids was determined, with average percentage reductions of 0.68%, 0.88% and 1.06% for the years 2027, 2033 and 2044, respectively.

Finally, it was determined the viability of the planning results with the incorporation of Photovoltaic Distributed Generation in the Low Voltage Grid, the investment costs amount to US$ 134,120.47, the NPV of 678,519.07 and the IRR of 50.86%, which indicate that alternative 1 is economically profitable and technically feasible.

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