Impact of Photovoltaic Systems Placement, Sizing on Power Quality in Distribution Network

Armend YMERI, Saša MUJOVIC
Univerisity of Montenegro, Faculty of Electrical Engineering Podgorica, 81000, Montenegro
sasam@ac.me

***Abstract*—The paper presents a Decision Tree Algorithm for impact of photovoltaic systems placement and sizing in order to improve power quality in distribution networks. The proposed approach is based primarily on ID3 and J48 Decision Tree Algorithms. With these algorithms, for different sizes of photovoltaic systems, can be defined the optimal location as well as minimal power losses of the distribution network. The simulations were carried out with real data obtained from the Kosovo Distribution Network and visualized with WEKA Toolbox. The obtained results compared with Genetic Algorithm MATLAB toolbox and DIGSILENT/Power factory software, prove that the Decision Tree Algorithm works well with an excellent and fast accuracy. The results from the application of the proposed method showed reduced power losses and optimal location in the distribution network confirmed method's validity. This approach can be used by engineers, electric utilities and distribution network operators for a quick decision with more efficient integration of new photovoltaic systems in the current distribution networks.**

***Index Terms*—distributed power generation, genetic algorithms, photovoltaic systems, power quality, power systems.**

I. INTRODUCTION

Distributed power generations are small electricity producers located near the consumption and load. Their production capacities can range from several kW to several MW and are directly connected to the distribution radial network. Distributed generations (DG) can be classified into four categories:

1. Micro DG with a power capacity of 1 W – 5 kW,
2. Small DG with a power capacity of 5 kW - 5 MW,
3. Medium DG with a power capacity of 5 - 50 MW,
4. Large DG with a power capacity of 50 - 300 MW.

DG is not a new concept and by definition, small size generator. The main idea behind a DG is that generation is done in a small scale and can be easily placed closer to the point of consumption [1]. The presence of the DG changes the power flow and load characteristics of the distribution network. It gradually becomes an active load network. A critical review of the various impacts, such as technical, economic and environmental resulting from the integration of DG in the distribution network as in [2].

DG has the potential to reduce emissions and increase dependence on alternative energy sources and hence, participate at energy diversification. It also helps to deliver backup power during the times of increased electricity demand, having also as a result the reduction of the distribution power losses [3].

An analysis for DG planning, optimal sizing and location is made on the basis of power loss minimization, system cost minimization and system energy loss minimization [4]. Usually, DGs are integrated with the existing distribution system and a lot of studies are done to find out the best location and size of DGs to produce the highest benefits.

Different technologies are used for DG sources such as Photovoltaic (PV) systems, wind generation, combustion engines, fuel cells, etc.

The positive effects of PV systems on the distribution network are: Free solar energy, environmental friendliness avoiding emissions, the possibility to supply places where power systems have not been built, high reliability, easiness in use and low operating costs.

It is necessary for the development of the distribution network to predict, as accurately as possible, the impact of PV systems so that consumers could be provided with a satisfactory electricity quality and at the same time, strive to minimize the losses. Accordingly, the optimal allocation of PV systems and their sizing is pivotal and several approaches have been proposed in the literature.

Optimization is applied in the deregulated power industry finding the best allocation of DG and other devices. There are four major optimization techniques/methodologies available for the distribution system planning in the presence of DG as: Analytical approaches, Conventional optimization programming techniques, Artificial intelligent search techniques and Hybrid based techniques [5].

The analytical method is a simple and non-iterative approach which provides an approximate solution in case of complex problems. This method is not successful in finding solutions for real problems and as such, it is used in rare situations [6]. An analytical method described in [7] computes the optimal location and size of multiple DGs, considering also different types of DGs.

Conventional optimization programming techniques are very good at providing the optimal allocation of PV systems with same/different size in a distribution grid. These methods offer better solutions compared to analytical methods but calculation time is longer.

The digital simulation and electrical network calculation program DIGSILENT/Power factory, in [8] is used to analyze the impact of multi DGs in terms of power losses when they are employed in the distribution network. When the DG is installed close to a substation, active power line losses are reduced. However, if DG's capacity is large and is

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in a long distance from the substation, active power line losses tend to increase as in [9].

Artificial intelligent search techniques for planning of DG in distribution grid may offer flexible and simplified solutions with a compromise between solution quality and computation time. Artificial intelligent (Heuristic) methods usually give an almost optimal solution in cases when there is only one method, but they require high-tech efforts. These methods are used more in complex problems which cannot be well mathematically described or cannot be solved through conventional methods. The most frequently used techniques are the Genetic Algorithm (GA) and various practical heuristic algorithms. The GA offers a new and powerful approach to these optimization problems which are made possible by increasing the availability of high computers performance at relatively low cost, as in [10].

Meta-heuristic methods are algorithms that add a stochastic factor to the solutions they find. These algorithms are generally known as techniques that do not depend on the problem and do not take advantage of the problem particularities. A description of the main meta-heuristic methods implemented in the determination of the location and/or sizing of the DG, is given in [11].

Influences of DG on the losses after its connection to the distribution network is treated as a special load which can output as active power, as in [12]. However, in the practical application, DG cannot be simply treated as the load which can output active power.

The goal of the algorithm for the individual allocation of DG units based on average daily power consumption and production curves was the minimization of cumulative average daily active power losses [13]. Using the proposed algorithm, the obtained DG allocation results are more detailed and precise, which in turn can have a great importance in avoiding unnecessary and often quite considerable costs in the distribution system operator.

A hybrid of two or more approaches can, however, offer a better solution by incorporating benefits of each and discarding their draw-backs. An optimization method based on Artificial Neural Networks (ANN) and GA is proposed for the determination of size and location of DG in radial and network distribution systems as well as for the reduction of active power losses and voltage profile improvement. ANNs have the ability to solve non-linear mathematical problems extremely quickly and precisely [14].

GA MATLAB toolbox is used in [15] for determining the optimum number of DG units installed in the distribution network with optimal power losses. The best results are obtained with a combination of the three methodologies with proper ratios i.e. reconfiguration of the network, installation of capacitor banks and DG units, altogether leading to a total loss reduction and, at the same time, maintaining the minimum bus voltage profile and reducing branch currents.

GA has the ability to solve nonlinear mathematical problems extremely quickly and precisely. One of the main reasons for using GA is its effectiveness during optimization, especially in cases for various constraints. In [16], an optimization method based on GA MATLAB Toolbox is performed to demonstrate how successfully this method could be used to determinate the size and location of PV systems. At the same time, this method is used to demonstrate the reduction of active power losses and voltage drops.

A decision-making algorithm has been developed for the optimum size and placement of DG units in distribution networks [17]. The proposed algorithm has been tested on the IEEE 33-bus radial distribution system and the obtained results have been compared with those of earlier studies, proving that the decision-making algorithm is well working and has an acceptable accuracy.

The location of PV systems can be determined by the local conditions (land, users), as well as these conditions do not endanger the proposed optimal solution.

The proposed approach is an optimization technique for optimal allocation of the PV systems within the distribution network for the given capacity. The algorithm used in this approach can estimate the optimal location for PV systems and can find the optimum PV size to be installed based on the reduction of power losses.

This approach works well and has an acceptable accuracy and it has been tested on the real radial distribution system. The results obtained in this paper by using Decision Tree Algorithm are compared to the results provided by GA MATLAB toolbox, in a real-time case.

The paper is structured as follows: Problem Formulation presented in section 2; Decision Tree Algorithm for optimal placement and sizing of PV systems presented in section 3; Losses estimation by Decision Tree Algorithm presented in section 4, Application of Decision Tree Algorithm in Distribution system and comparison results presented in section 5; and Conclusions of this paper are summarized in section 6.

II. The Problem Formulation

The main goal of this paper is to study the optimal placement and sizing of PV systems based on the reduction of active power losses in the distribution network. Active power losses exist at generation, transmission and distribution systems. Most of them occur in the distribution systems because of the low voltage, high current levels and radial configuration of these systems [16].

A. Power losses analysis without DG

Power line losses occur when current flows through the distribution grid and they depend on the current amount and resistance. Referring to literature as in [11], [15], the mathematical model for the calculation of power line losses for the case without DG in the distribution line can be calculated by equation (1):

$$P_{LossL} = 3I_L^2 rL \tag{1}$$

where IL is the line current, r the line electrical resistance per unit of length, L the distance between substation and load.

Losses for a three-phase system without DGs can be expressed as in (2):

$$P_{LossL} = \frac{rL(P_L^2 + Q_L^2)}{3V_L^2} \tag{2}$$

where PL is the active power line, QL the reactive power line, VL the load voltage.

B. Power losses analysis with DG

When DG is connected in the distribution network, power losses are calculated by a combination of power line losses from the source to the DG *(P_{LossSG})* and power losses from the location of DG to the load location *(P_{LossGL})*, as in (3) and (4):

$$P_{LossSG} = \frac{rG(P_L^2 + Q_L^2 + P_G^2 + Q_G^2 - 2P_L P_G - 2Q_L Q_G)}{3V_L^2} \quad (3)$$

$$P_{LossGL} = \frac{r(P_L^2 + Q_L^2)}{3V_L^2}(L - G) \quad (4)$$

where PG is the active power of DG, QG the reactive power of DG, G the distance between substation and DG.

The total line loss (P_{LossAT}) in presence of DG can be calculated by combining equations (3) and (4) and are expressed as in (5):

$$P_{LosssAT} = \frac{rL[P_L^2 + Q_L^2 + (P_G^2 + Q_G^2 - 2P_L P_G - 2Q_L Q_G)\frac{G}{L}]}{3V_L^2} \quad (5)$$

Loss reduction or instantaneous loss savings ΔP_{LOSS} at any point on a feeder can be represented as the difference between losses without DG and losses with DG as in (6), (7) and they can be positive or negative:

$$\Delta P_{LOSS} = P_{LossL} - P_{LosssAT} \quad (6)$$

$$\Delta P_{LOSS} = \frac{rG(P_G^2 + Q_G^2 - 2P_L P_G - 2Q_L Q_G)}{3V_L^2} \quad (7)$$

When the loss in the system is reduced, then ΔP_{LOSS} has the positive sign and, if not, it is indicated with the negative sign. It indicates that DG causes the system loss to increase [18], [19].

If the location and installed power of the DG are chosen to fit the size and location of the load, it will help to reduce power losses in the line.

III. Decision Tree Algorithm for Optimal Placement and Sizing of PV Systems

Decision Tree Algorithms provide an effective method of Decision Making because it clearly lays out the problem so that all options can be challenged. This method allows analyzing fully the possible consequences of a decision and provide a framework to quantify the values of the outcomes and the probabilities of achieving them.

Decision Tree is a popular classifier that does not require any knowledge or parameter setting. The approach is a supervised learning. Given a training data, we can induce a Decision Tree. From a Decision Tree, we can easily create rules about the data. Using Decision Tree, we can easily predict the classification of unseen records.

Decision Tree is a hierarchical tree structure that used to classify classes based on a series of questions (or rules) about the attributes of the classes. The attributes of the classes can be any type of variables from binary, nominal, ordinal and quantitative values. While the classes must be of qualitative type (categorical or binary, or ordinal).

Decision Tree builds classification or regression models in the form of a tree structure. It breaks down a dataset into smaller subsets while at the same time an associated Decision Tree is incrementally developed. The final result is a tree with decision nodes and leaf nodes. A decision node has two or more branches. Leaf node represents a classification or decision. The topmost decision node in a tree which corresponds to the best predictor called root node. Decision Trees can handle both categorical and numerical data.

The general motive of using Decision Tree is to create a training model which can be used to predict the class or the value of target variables by learning the decision rules inferred from prior data (training data). The Decision Tree Algorithm tries to solve the problem, by using tree representation.

The main goal of regression algorithms is to predict the discrete or a continuous value. In our case, the problem deals with continuous values.

The core algorithm for building Decision Tree used in this paper is based on ID3 and J 48 that uses Entropy and Information Gain to construct a Decision Tree.

A. Entropy

A Decision Tree Algorithm is built top-down from a root node and involves partitioning the data into subsets that contain instances with similar values (homogenous). The ID3 and J48 algorithms use entropy to calculate the homogeneity of a sample. If the sample is completely homogeneous the entropy is zero and if the sample is an equally divided it has an entropy of one. Entropy calculation is presented in (8).

$$H(x) = E_x[I(x)] = -\sum_{x \in X} p(x) \log p(x) \quad (8)$$

B. Information Gain

By using information gain as a criterion, we try to estimate the information contained by each attribute.

By calculating entropy measure of each attribute we can calculate their information gain. Information gain calculates the expected reduction in entropy due to the sorting on the attribute. Information gain can be calculated.

The information gain is based on the decrease in entropy after a dataset is split on an attribute. Constructing a Decision Tree is all about finding an attribute that returns the highest information gain (i.e., the most homogeneous branches).

Decision Trees Algorithm often mimic the human level thinking so it is so simple to understand the data and make some good interpretations.

The next step to determine the correct solution for minimizing active power losses is to choose the appropriate location and size of PV systems for implementation. This is done by using the above-explained Decision Tree Algorithm as presented in Fig. 1.

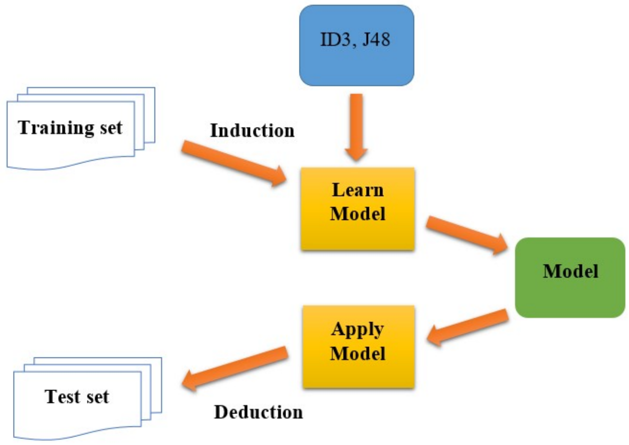

Figure 1. Flowchart of the Decision making algorithm

IV. LOSSES ESTIMATION BY DECISION TREE ALGORITHM

In order to achieve the best location and sizing of PV systems in the distribution network as minimal power losses in 10 kV line, the ID 3 and J 48 algorithms are applied on a part of distribution grid of KEDS (Kosovo Electricity Distribution and Supply), as presented in Table I.

TABLE I. DATA OF 10 KV LINE

Terminal	Distance (km)	Load (MW)
1	3.35	0.012
2	4.62	0.198
3	1.7	0.503
4	6.36	0.775
5	9.99	1.076

The length of 10 kV line "Muciverc" is L =26.02 km and total peak power demand in this line is 2.564 MVA [20]. Based on the simulation carried out during September 2013, by running the power flow calculation in DIGSILENT/Power factory software, the results of power line losses in the case without PV systems are ΔP=0.4514MW as shown in Table II.

TABLE II. POWER LOSSES WITHOUT PV SYSTEMS

Terminal	Losses
1	0.0000008
2	0.00551
3	0.0107
4	0.101
5	0.334
Total:	0.451

When a PV system is connected in a terminal of the 10 kV line "Muciverc" with installed capacity of PV systems from 0.4 MW to 4 MW is presented in Fig. 2.

According to data from calculation in DIGSILENT/Power factory software, the results of power line losses in all terminals by changing the location of the PV systems but keeping the same size, in four cases (0.4 MW, 1 MW, 2 MW and 4 MW) are smaller than in the case without PV systems, as shown in Table III.

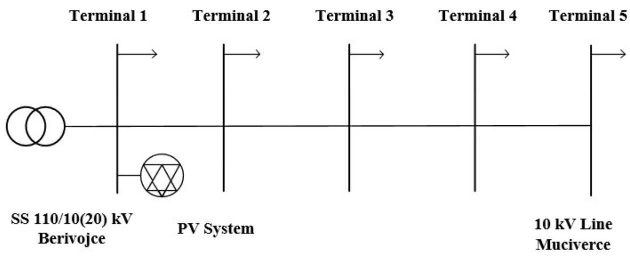

Figure 2. Single line diagram of 10 kV line with PV Systems

TABLE III. POWER LOSSES WITH PV SYSTEMS

Terminal	PV capacity 0.4 (MW)	PV capacity 1 (MW)	PV capacity 2 (MW)	PV capacity 4 (MW)
1	0.442	0.431	0.423	0.438
2	0.429	0.404	0.383	0.421
3	0.424	0.394	0.368	0.414
4	0.406	0.356	0.314	0.390
5	0.401	0.344	0.297	0.383

In order to achieve the best location of PV systems in the distribution network for the given active power losses and for PV system capacity, we use a Decision Tree approach.

Firstly, we define our training data with two attributes PV capacity and P_{LOSS} and Terminal as a decision class. The values for the attributes are presented in Fig. 3 for PV apacity = {VLC, LC, MC, OC, HC} and P_{LOSS} = {L, M, H, EH}.

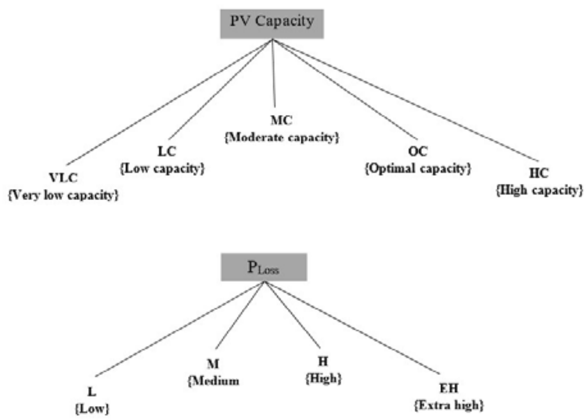

Figure 3. Attributes of ID 3 Algorithm

Since we are dealing with continuous training data, we apply Global Discretization process for P_{LOSS} as presented in Table IV.

TABLE IV. GLOBAL DISCRETIZATION FOR P_{LOSS}

Attribute	P_{LOSS}	Range
EH	Extra high	ΔP>0.414
H	High	0.414>=ΔP>0.383
M	Medium	0.383>=ΔP>0.297
L	Low	0.297=ΔP

Global Discretization process for PV capacity is presented in Table V.

TABLE V. GLOBAL DISCRETIZATION FOR PV CAPACITY

Attribute	PV Capacity	Range
VLC	Very Low Capacity	0<PV<=0.4
LC	Low Capacity	0.4<PV<=1
MC	Moderate Capacity	1<PV<=2
OC	Optimal Capacity	2<PV<=2.564
HC	High Capacity	2.564<PV<=4

For a demonstration, we will show some of the training data in Table VI.

TABLE VI. SET OF TRAINING DATA

PV Capacity	P_{LOSS}	Classes (terminal)
MC	L	Five
MC	M	Four
LC	M	Five
LC	M	Four
MC	M	Three
HC	M	Five
MC	M	Two
HC	H	Four
LC	H	Three
VLC	H	Five
LC	H	Two
VLC	H	Four
HC	H	Three
HC	EH	Two
MC	EH	One
VLC	EH	Three
VLC	EH	Two
LC	EH	One
HC	EH	One
VLC	EH	One
OC	L	Five

Based on these training data we can induce a decision tree as in Fig. 4.

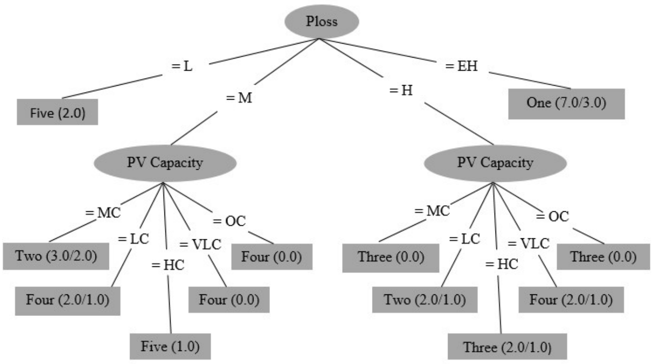

Figure 4. Visualized Decision Tree algorithm

V. APPLICATION OF DECISION TREE ALGORITHM IN DISTRIBUTION SYSTEM AND COMPARISON OF RESULTS

Decision Tree Algorithm and GA MATLAB toolbox use the same database. By running Decision Tree Algorithm on a set of variables for a selected terminal and by running the power flow calculation in DIGSILENT/Power factory and GA MATLAB toolbox with the same PV systems values, the results can be compared and evaluated. We use the real case scenarios data, based on the simulation by running the power flow calculation in DIGSILENT/Power factory and GA MATLAB Toolbox.

GA MATLAB toolbox has reached an optimal solution with 50 iteration (see Table VII). According to the outputs, the optimal location for a PV system is terminal 5, while the values for the corresponding size and total power losses for the given load are 2.564 MW and 0.248 MW, respectively.

TABLE VII. GA ALGORITHM OUTPUTS

GA Outputs	Best Value
PV System capacity (MW)	2.564
Active Power Losses (MW)	0.248

The performance of the Decision Tree Algorithm is acceptable. The comparison of the results given by GA MATLAB toolbox show that the Decision Tree determines the valid value of active power losses. The results of the Decision Making, generally match the results provided by GA MATLAB toolbox. The results are compared by calculating each terminal with different PV systems capacities (from 0.4 MW to 4 MW).

In particular, the experimental data for the cases with PV Systems are used as training data for our Decision Tree Algorithm, as in Fig. 5.

Terminal	Power Losses (MW) PV Systems capacity			
	0.4 MW	1 MW	2 MW	4 MW
1	0.442	0.431	0.422	0.438
2	0.429	0.404	0.382	0.420
3	0.424	0.394	0.368	0.414
4	0.406	0.356	0.313	0.390
5	0.401	0.344	0.297	0.382

Terminal	Power Losses (MW) PV Systems capacity			
	VLC	LC	MC	HC
One	EH	EH	EH	EH
Two	EH	H	M	EH
Three	EH	H	M	H
Four	H	M	M	H
Five	H	M	L	M

Figure 5. Decision Tree data converted from DIGSILENT/Power factory

In order to compare the data from DIGSILENT/Power factory and our new approach Decision Tree Algorithm, firstly, we convert the results from TABLE III into Decision Tree data format, as in Fig. 6.

In ID3 J48 Algorithm for simulation results we used WEKA machine learning software.

Based on these tools we will see that on the same terminal e.g. terminal 5, power losses Low category (0.297=ΔP) for each PV Capacity. Also, we will see that in terminal 1 we will see losses of Extra High category (ΔP>0.414) for each capacity of PV systems. The best case is when the PV systems are connected to terminals 3 and 4 for optimal capacity (OC) of PV systems.

From the Fig. 6 can be verified the correctness of the Decision Tree Algorithm used in this paper. In cases where the comparing of results yield a “Correct” answer, it means that the Decision Tree output is 100% correct. In cases where comparing of results yield a “Correct?” answer, it means that the training data are somehow “poor” and additional data should be taken in consideration after which probably the answer will be “Correct”.

PV load and source have relatively large variations in both day and year, but it does not affect in terms of the optimization approach validity.

Decision Tree			Comparing with DIGSILENT/Power factory/ GA MATLAB Toolbox
Attributes		Classes	Classes
P_{Loss}	PV Capacity	Terminals	Terminals
EH	VLC	One	Correct
EH	LC	One	Correct
EH	MC	One	Correct
EH	OC	One	Correct?
EH	HC	One	Correct
L	VLC	Five	Correct?
L	LC	Five	Correct?
L	MC	Five	Correct
L	OC	Five	Correct?
L	HC	Five	Correct?
M	MC	Two	Correct
M	LC	Four	Correct
M	HC	Five	Correct
M	VLC	Four	Correct?
M	OC	Four	Correct?
H	MC	Three	Correct?
H	LC	Two	Correct
H	HC	Three	Correct
H	VLC	Four	Correct
H	OC	Three	Correct?

Results from DIGSILENT/Power factory/ GA MATLAB Toolbox		
Attributes		Classes
P_{Loss}	PV Capacity	Terminals
EH	VLC	One
EH	VLC	Two
EH	VLC	Three
H	VLC	Four
H	VLC	Five
EH	LC	One
H	LC	Two
H	LC	Three
M	LC	Four
M	LC	Five
EH	MC	One
M	MC	Two
M	MC	Three
M	MC	Four
L	MC	Five
EH	HC	One
EH	HC	Two
H	HC	Three
H	HC	Four
M	HC	Five

Figure 6. Comparing of results from Decision Tree and DIGSILENT/Power factory

VI. CONCLUSION

The impact of PV Systems on distribution networks needs to be properly evaluated and rated in order to achieve the greatest benefit for the distribution network. An optimization method based on Decision Tree Algorithm is performed in this paper to demonstrate how successfully this method could be used to determinate the optimal location of PV systems for a given capacity.

The power flow is provided by using DIGSILENT/Power Factory and optimization problem solved using GA MATLAB toolbox since it has the ability to solve nonlinear mathematical problems extremely quickly and precisely. These results are verified using Decision Tree Algorithm.

The comparison has shown that the proposed algorithm is efficient and can provide good solutions for the optimum placement of PV Systems in distribution networks. The Decision Tree Algorithm is well working and has a very good accuracy. The main challenge consists of the proper training data.

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