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Power loss and voltage variation in distribution systems with optimal allocation of distributed generation

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***Abstract*—This article presents a methodology for optimal distributed generation (DG) allocation and sizing in distribution systems, in order to minimize the electrical network losses and keep acceptable voltage profiles. The optimization problem considered equality and inequality constrains, 24 hours power load levels, operational voltage limits, conventional power flow, DG placement with binary variables and sizing of active and reactive power. The optimization problem is solved by mixed integer nonlinear programming (MINPL) using KNITRO solver.**

***Index Terms*—DG placement and sizing, MINPL, power loss, smart grid, voltage variation.**

I. INTRODUCTION

The distributed generation (DG) is characterized by the installations of small sources in different locations of the system, trying to be as close to the final consumer in order to get benefits in power quality [1]. In the last years, the increase of DG installation brought up different issues in the energy industry, scientific community, economic and environmental policy management. This form of power generation has been contributing for the development of new green supplies, which is a way to diversify energy sources from the main hydro and thermal power [2]. The impact of DG on a smart grid is a big challenge for power systems and especially when the integration of DG is based on renewable energy sources (RESs) [3]. The DG power injection may change the power flow course in the distribution feeder [4]. The DG allocation and sizing are decisive to keep acceptable levels in the power quality of the electrical power system, because it improves the power quality reducing loss and distribution cost. On the other hand, bad allocation may cause undesirable effects [5]. Therefore, it is very important to use an optimization method capable of obtaining the best possible solution [6].

The smart grid concept facilitates energy management and ancillary services, and increases reliability. In Brazil DG is defined by decree 5163 from 2004, which proposes that it is considered as DG the electricity produced by a utility or authorized agents connected directly to the electrical distribution system [7]. In the distribution level the micro-grids may be connected to the distribution feeder and receive some ancillary energy benefits in case the DG produces more energy than the owner uses [8].

Currently many optimization techniques are being implemented to find out how to integrate the DG with the power system more efficiently [2] using adequate power injection to improve the power quality. In this context, this paper proposes a novel optimization approach that considers a 24-hour power load to locate and size the DG.

II. OPTIMIZATION MODEL

The optimal DG placement goal is to look for the best location and power size to minimize power losses and keep voltage variation in acceptable levels considering discrete 24 hours power levels and the desirable electric power system operational constrains.

A. Objective function

The objective function may be either single or multi-objective. The multi-objective can be represented by the sum of two single different objectives but linked by unit normalization weight constant, allowing the objective variables sum in the same units. The objective function (1) is formed by the sum of each power load level of active power losses (2).

$$Objective = \min\left(\sum_{i=1}^{24} P_i^L\right) \quad (1)$$

$$P_i^L = P_{V\theta} + \sum_{k=2}^{n} P_k^{DG} - \sum_{k=2}^{n} P_k^{load} \quad (2)$$

Where:

n: Total number of buses.

$P_{v\theta}$: Utility active power injection (MW).

P_k^{DG}: DG active power injection (MW).

P_k^{load}: Load active power (MW).

B. Constraints

The electrical model constraints are the equality power flow; see (3) and (4), which evaluates the systems estimation error. The voltage limits, DG power factor, active, reactive and apparent power limits are in accordance with the solution for the problem, as can be seen in TABLE I.

$$\Delta P_k = \beta_k * P_k^{DG} - P_k^{load} - P_k^{cal} = 0 \quad (3)$$

$$\Delta Q_k = \beta_k * Q_k^{DG} - Q_k^{load} - Q_k^{cal} = 0 \quad (4)$$

Where:

ΔP_k: Active power flow estimation error (MW).

P_k^{cal}: Calculated active power injection (MW).

ΔQ_k: Reactive power flow estimation error (Mvar).

Q_k^{DG}: DG reactive power injection (Mvar).

Q_k^{load}: Load reactive power (Mvar).

Q_k^{cal}: Calculated reactive power injection (Mvar).

β_k: Binary DG variable, 1 means DG in bus k.

TABLE I. LIMITS FOR EACH VARIABLE.

Variable	Minimum	Maximum
V_k	0.93 (pu)	1.05 (pu)
$\sum_{k=1}^{n} P_k^{DG}$	0	S^a (MVA)
$\sum_{k=1}^{n} Q_k^{DG}$	- S^a (MVA)	S^a (MVA)
$\sum_{k=1}^{n} S_k^{DG}$	0	S^a (kVA)

a..V_k voltage bar k.

C. Metodology

The data of the power system is inserted in MATLAB. The algorithm generates the admittance matrix and writes all variables, constraints and equations of the 24 load levels as a text file in general algebraic modeling system format (GAMS). Then, this model is sent to NEOS Server to be processed by the KNITRO solver [10]. This process is illustrated in Fig. 1.

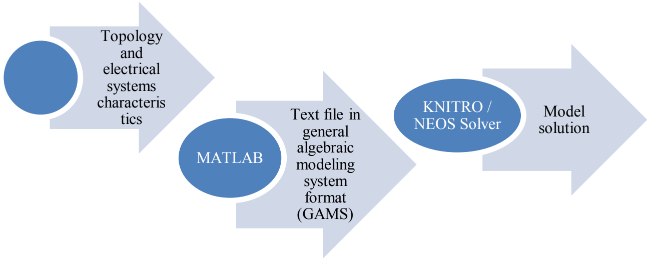

Fig. 1. Optimization methodology process.

III. CASE STUDY

The simulated system is shown in Fig. 2. This system is a modification of IEEE 33 bus [11]. The substation is in node number one and it is modeled as PVΘ bus. The nominal voltage is 12.66kV and the apparent power base is 10MVA.

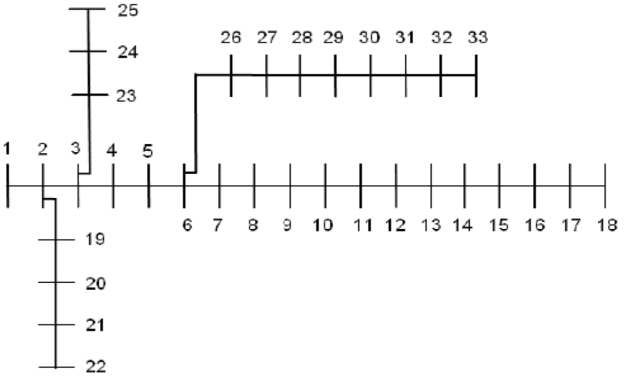

Fig. 2. Simulated system topology.

In Fig. 3, the 24 voltage levels of each bus without DG can be observed. It is noticeable that many voltage profiles trespass the minimal acceptable voltage limit (0.93pu). Considering the topology and the electric circuit characteristics, the worst values can be seen in the farthest buses from the reference bus.

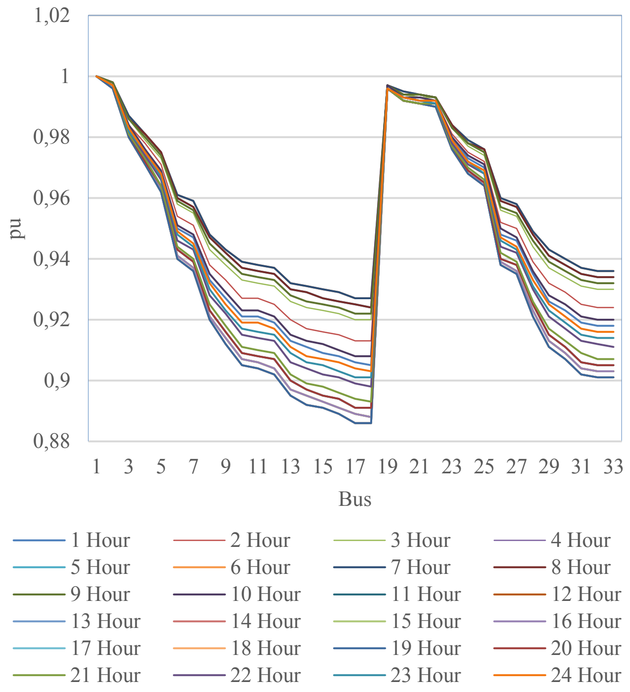

Fig. 3. System voltage profile without DG.

The power losses without DG for every hour can be observed in Fig. 4. The optimization model uses a discrete 24-hour demand curve as shown in Fig. 5 where the total load peak is 510 kVA and the minimum load level is 340 kVA. Each point in the curve represents the total apparent power load for each hour of day.

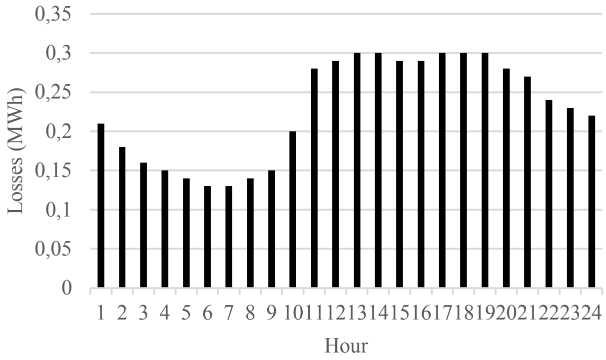

Fig. 4. System Active losses for each hour without DG.

As expected the heavy load levels increase the losses for all buses in the system. The total loses for the 24 hours is 5.48 MWh.

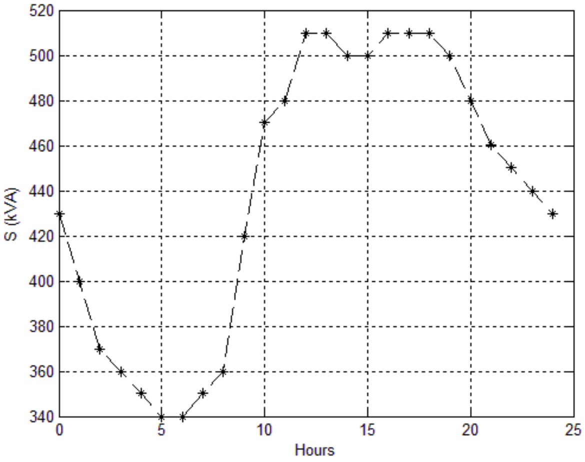

Fig. 5. 24-hour apparent power load.

IV. RESULTS AND DISCUSSIONS

In order to show the results it is very important to note that for this entire section the total power load is the curve shown in Fig. 5. Fig. 6 presents the value of the objective function for an optimal DG in each bus. The bus number 6 offers the best possible place to insert a DG to minimize losses. There are other buses close to the optimal solution that represents a suitable place to insert a DG; some of them offer acceptable voltage limits and similar losses. For this reason, the buses, which are not shown in this figure, are not suitable because they exceed the acceptable voltage limits.

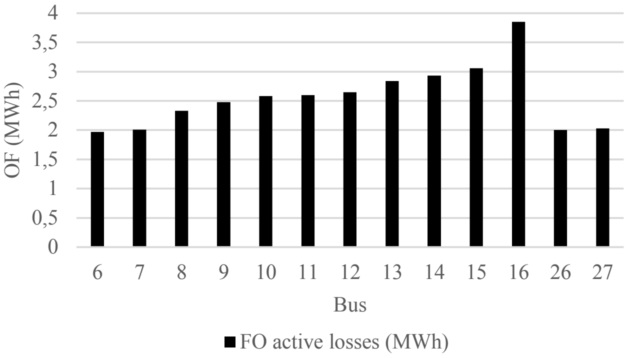

Fig. 6. Optimal objective function in each bus.

Fig. 7 shows the optimal active and reactive power injection for each bus supposing a DG is in operation. The limitation of the DG injection is due to the operational constraints established for the optimization problem. A relaxation of the constraints permits to increase the power injected. There is a link between the increase of DG injection and lower losses. According to their location, some buses may inject more power and reduce the losses.

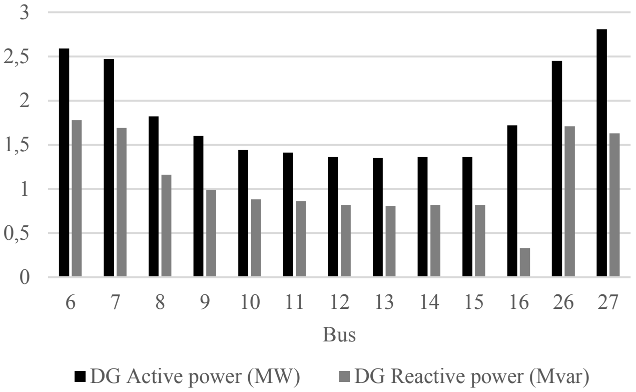

Fig. 7. Optimal DG power injection for each bus.

Fig 8 shows the voltage profile of system buses with optimal DG allocation in bus number 6. In this case such bus is in a strategic position, because some lines are connected to it, improving the voltage in the neighboring buses. The bus located at the end of the lines (18 and 33) have the worst voltage amplitude, but in the 24-hour power load the minimal voltage limit has not been exceeded. It is clear that the optimal placement and sizing of DG improve the voltage profile and minimize active power losses as shown in TABLE II.

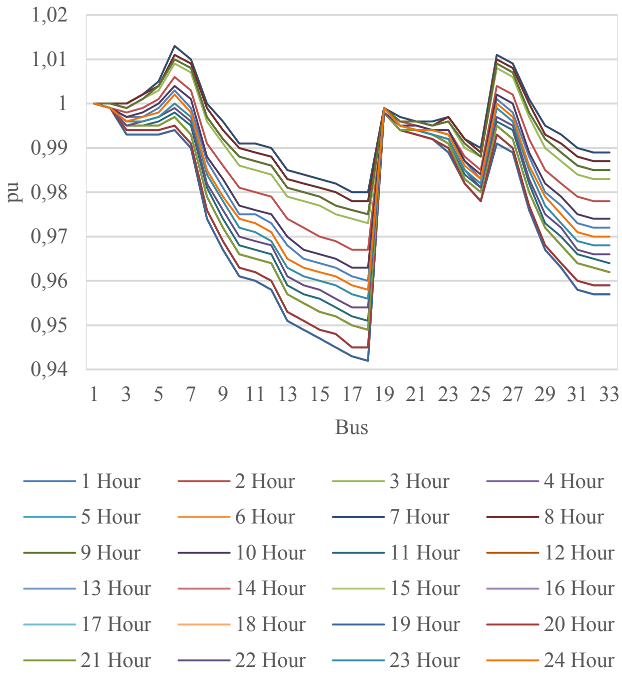

Fig. 8. System voltage profile with optimal DG in bus six.

Fig. 9 shows the losses for each hour when a DG is located in bus 6. The losses behavior is very similar to Fig. 4, but the amplitude is lower, as expected.

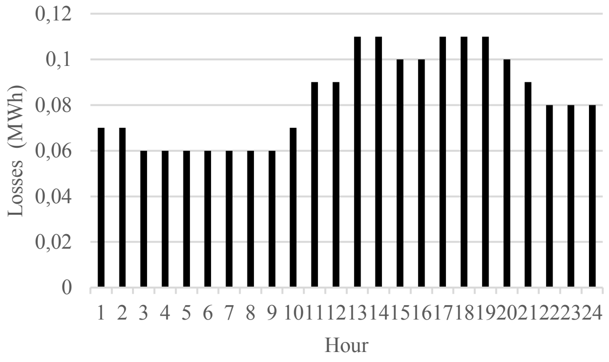

Fig. 9. System Active losses for each hour with optimal DG at bus 6.

TABLE II shows the comparison between the case without DG and with DG allocated in every possible bus. The count of losses is the sum of all 24-hour levels and the value of reduction corresponds to the difference between the values with or without DG, most of the allocation results in a loss reduction of about 50%.

TABLE II. LOSSES REDUCTION WITH DG.

Bus k	Losses without DG (MWh/day)	Losses with DG in bus k (MWh/day)	Reduction (%)
6	5,48	1,97	64,05
7		2,01	63,32
8		2,33	57,48
9		2,48	54,74
10		2,58	52,92
11		2,6	52,55
12		2,65	51,64
13		2,84	48,18
14		2,93	46,53
15		3,06	44,16
16		3,85	29,74
26		2	63,50
27		2,03	62,96

TABLE III shows the comparison between different numbers of DG allocated in the system. Optimal placement of more than one DG may reduce power losses and keep the voltage in an acceptable profile.

TABLE III. RESULTS FOR OPTIMAL DG CONSIDERING ONE OR MORE DG.

Number of DG allocated	Position bus	OF (MWh/day)	DG (MW)	DG (Mvar)
1	6	1,97	2,59	1,78
2	11	0,95	0,97	0,46
	30		1,07	1,02
3	10	0,63	0,93	0,42
	24		1,01	0,41
	30		0,98	0,97
4	15	0,51	0,64	0,29
	25		0,76	0,32
	26		0,75	0,30
	30		0,77	0,89
5	2	0,60	0,26	0
	15		0,74	0,35
	25		0,84	0,42
	30		0,75	1,04
	33		0,32	0

Fig. 10 shows the losses reduction considering different numbers of DGs. The percentage of reduction increases and reaches a peak when the number of DGs is four, after that it stars to decrease for this case.

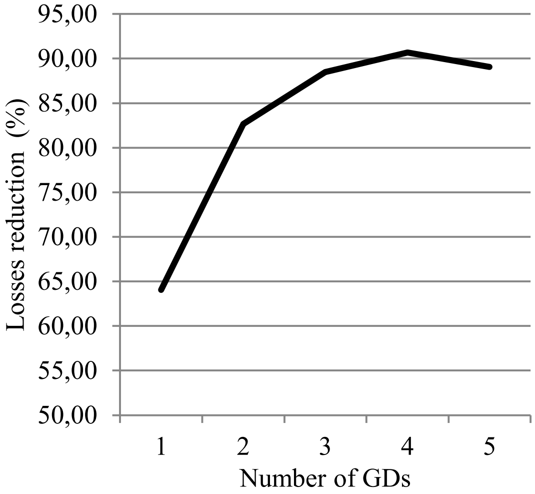

Fig. 10. Losses Reduction with multiple DGs.

V. CONCLUSION

This work proposed a novel optimization model based on losses minimization in order to place and size the DG in the system considering 24-hour power loads and acceptable voltage limits. The case studied shows that the proposed model can minimize losses keeping voltage variation within the desired limits. The proposed method has been extensively simulated considering an IEEE 33 bus radial distribution system. Among all the constraining factors introduced in the proposed fitness function and the inclusion of more than one DG in the system, the study demonstrated a considerable losses reduction.

In practice, the choice of the best site may not be feasible due to technical restrictions and economic resources. However, the optimization and analysis presented here may help the utility managers to decide on the best option for placement and sizing of DG units.

The future scope of this paper will focus on the inclusion of power quality requirements in the objective function and how the placement of DG can reduce costs for the power company.

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