18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

Losses allocation due to penetration of DG and self-consumption operation in distribution systems. Case: PV Solar Energy

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Abstract. This paper deals the losses allocation in distribution systems with distributed generation (DG). From an analysis based on marginalist theory for costs, losses are assigned simultaneously to generators and consumers of electricity. Taking into account, measurement samplings each 15 minutes during a typical day, it is presented an allocation proceeding of losses along the time, managing profiles of demand and generation by voltage levels. The allocation coefficients are calculated from series of power balance with shared self-consumption and power surpluses towards neighboring nodes. It was simulated through a quasi-static modeling for a network of Medium Voltage and Low Voltage, for different levels of penetration PV Solar. It is presented as an alternative for efficient allocation of losses using the Colombian case as study reference.

Key words- Distributed Generation; Self-consumption; losses allocation; network monitoring.

1. Introduction

Studies have indicated that inappropriate selection of location and size of DG, may lead to greater system losses than the losses without DG [1].
Since system losses represent a considerable cost for utilities, traditionally, the regulatory allocation of electrical losses has been discussed as belonging of the system load. That is, the technical losses produced along the supply chain of a distribution network are accumulated and prorated towards the demand of users, among others, with tariff purposes [2, 3]. Therefore, if a DG unit reduce an amount "X" of losses, it is fair that the owner of the distributed plants receives incentives of participation; otherwise, it should to assume charges for increased losses, an unusual case, which may represent a practice signal to limit the power hosting capacity on the network.
Certain distribution network operators (DNOs) require that the interconnection of DG does not lead to an increase of network losses [4].

In the literature, there are several methods of allocation of losses that have been applied in transport, and now, in distribution networks [5, 6, 7]. Conceptually, the allocation of losses is different that its determination. In this approach, once the calculation or modelling to quantify losses has been achieved, then they are assigned.

In this paper, self-consumption represents the nodal model of power balance and starting point for the proposed procedure. Then, the behaviour of the power curve by injected surpluses to the grid is sensitivity pattern on the variation of the total losses, during a typical day.
Surely, it is necessary to measure separately the demand profiles and PV solar generation profiles, for its respective modeling as input data. That is, this approach is not performed from the prediction but during the operation of distribution networks.
Moreover, as is known that not all the time there is power injection by DGs. In case of PV Solar energy as indicated in [8], variations in irradiation at timescales of seconds and minutes are due to shading e.g. the passing of clouds. This last effect was studied with more detail in [9].
Additionally, time series analysis to determine % observable improvement in feeder response under various smart inverter function implementation [10].
On the analysis, the maximum PV size is restricted by the customer peak load and size of the service transformer. The solar peak maximum and minimum loads determine more probable bounds for the circuit response [11]. Here it is proposed to do it from the injection of surpluses every 15 minutes for short-term scheduling as in [12], selected time in order to verify a review with measurement and possible changes on magnitude of injected power by shadows or cloud passes.
In this paper, it proposed a losses allocation proceeding along the time, which is validated for a test network for Medium Voltage (MV) and Low Voltage (LV), with similar features of the Colombian electrical system. This proposal of losses allocation is modelled through a quasi-static simulation, where the demanded power or generated by DG users determines their responsibility on losses, according to connection level.
In general, a brief summary of criteria for loss allocation procedures is presented in the section 2, followed by a regulatory description of the Colombian case regarding the allocation of efficient losses in section 3. In section 4, the proposed procedure is illustrated and allocation coefficient

curves are obtained during a consumption day, using different penetration levels of PV Solar. It is applied a quasi-static modelling to simulate shared self-consumption. Finally, the efficient allocation of losses is achieved and certain advantages of application to the network operation are appointed, providing critical evidence of its temporary monitoring.

2. Criteria for procedures of losses allocation

Among the allocation procedures found, there are Pro Rata procedures [13], proportional allocation procedures [7, 14] and marginal procedures [5]. Another revised classification indicates that there are direct and indirect procedures [15], which is related to the calculating method of losses for accurate modelling. There are studies whose approach performs comparisons between the different methods, with advantages and disadvantages [16, 17, 13].

Nevertheless, no method is better than another. Its establishment depends on the needs of the network operator and the resources available to obtain the measurement information in the system.

In order to obtain an efficient loss allocation, it is necessary to establish minimum criteria that any type of procedure must meet [15]: to reflect the true cost that each user imposes on the network with respect to cost of losses; accuracy, consistency and equity: must avoid or minimise cross subsidies between users and between different times of use. Furthermore, the method must be consistent; must utilise metered data: from a practical standpoint, it is desirable to base allocation of losses on actual metered data; and by last, any proposed allocation must be simple and easy to implement.

3. Efficient loss allocation

For the Colombian regulation, efficient technical losses correspond technical energy losses at voltage levels 2, 3 and 4[1] approved in the particular resolutions that approve usage charges based on Resolution CREG 097 of 2008. At voltage level 1 it is the sum of the technical energy losses plus the recognized non-technical losses.

3.1. Calculation of Balance Sheets by DNO and useful energies

Considering the input energy at a voltage level, product of the previously performed balances, and the loss rate of the same level, the useful energies of voltage levels 4, 3, 2 and 1 are determined according to the following expression [18]:

$$\boldsymbol{Eu_{j,n} = EE_{j,n} * \left(1 - P_{j,n}\right)} \quad \text{(Eq. 1)}$$

Where: $Eu_{j,n}$: Useful Energy of Voltage Level n, of DNO j.

$EE_{j,n}$: Input energy at Voltage Level n, from DNO j,

$\boldsymbol{P_{j,n}}$: Percentage of recognized losses at Voltage Level n, from DNO j

The allocated percentage of recognized losses is data that arises from the information supplied by the system network operators to the Regulation Commission (CREG).

The commission CREG publishes periodically the losses index $\boldsymbol{P_{j,n}}$ for all the DNOs. According to [19] , calculating a national average Index for network operators by each voltage level: $\boldsymbol{P_{j,1} = 9,46\%}$ $\boldsymbol{P_{j,2} = 1,48\%}$ $\boldsymbol{P_{j,3} = 1,85\%}$ ***and*** $\boldsymbol{P_{j,4} = 0,91\%}$.

4. Allocation Procedure of Losses in Time

Conceptually, loss allocation is a difficult task, because losses in the distribution system branches are nonlinear functions of generations and loads. It is impossible to calculate the exact amount of losses in advance, without running a power flow [20].

In fact, power flows are governed by non-linear equations, it is not possible to break down exactly the flow of a line as a sum of partial flows due to the injection of each node **[3]**. The sum of losses by a feeder due to several loads does not comply with the principle of overlapping, meaning it is not equal to the sum of the losses caused on the feeder by each load individually. A loss allocation analysis on an individual assembly of a DG unit by substitution is not feasible when performing loss allocation and do not prevent temporal and spatial cross-subsidies [15, 20].

In the analysis, demand masking is examined by correlating measured solar irradiance data with measured feeder load. Change in net demand will also affect feeder losses and consumption [21].

Besides, to analyze the variation on the amount of losses between a scenario with an installed DG and another, without DG, the new elements aggregated to network are not unique cause of marginal amount of losses, but its interaction with the demand and generation on the existing network explains the total losses.

All generators DGs within a topologically connected zone in its aim feeder and secondary voltage level of the transformer will have the same loss coefficient value. The assigned loss value will vary depending on size of each unit. The amount of system losses at any point in the steady state is due to the flow and consumption of power to and from ending branches of the network, depending the location and sizing of DG.

Understanding the Colombian regulation, a complementary model for allocation is proposed as described in Figure 1, in order to quantify technical losses by medium and low voltage zones, and to have a comprehensive causality criterion on total network losses.

In fact, the form of redistribution of losses must satisfy the following expression between DGs and demand:

$$\boldsymbol{L = \sum_{i=1}^{n} L_{Gi} + \sum_{i=1}^{n} L_{Di}} \quad \text{(Eq. 2)}$$

Where: L are total losses of active power. L_{Gi} are losses of active power allocated for generator i. L_{Di} are losses of active power allocated to demand of users.

[1] ***Note:*** *Resolution CREG 082/2002. The voltage levels are: NT1 (<= 1000V), NT2 (> 1000V and <= 30 kV), NT3 (> 30kV and <= 57.5kV) - belong to SDL-, and NT4 (> 57.5kV and <= 220kV) below to STR.*

The application on intervals of consecutive times, of the equation, during a period of time, allow to allocate losses of energy in that period [17].
The losses are assigned under the representative scheme in the following block model in figure 1, the energy that comes from the transmission network (STR) is injected through the transformer from high to medium voltage (from STR to MV Zone at SDL, local distribution system), whose losses are assigned to the secondary, that is, at the medium voltage level. Then, global losses are reflected into the demand, include losses by transformation and set of lines of medium voltage and low voltage of each zone [22].
Equations 3 and 4, sum energy flows (E) between commercial boundaries to get losses in the distribution network.

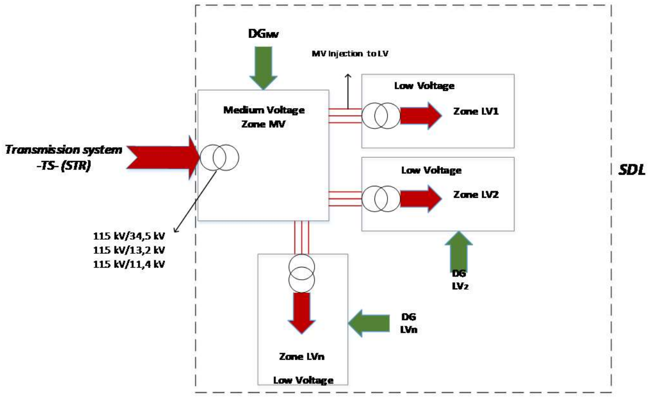


Figure 1. Model for allocation of losses.

$$\boldsymbol{Losses\ in\ LV} = \boldsymbol{E_{from\_MV}} + \boldsymbol{E_{DG\_LVn}} - \boldsymbol{E_{LVn}} \text{ (Eq. 3)}$$

$$\boldsymbol{Losses\ in\ MV} = \boldsymbol{E_{ts}} + \boldsymbol{E_{DG_{MV}}} - \boldsymbol{E_{MV}} - \boldsymbol{E_{LV1}} - \boldsymbol{E_{LV2}} - \boldsymbol{E_{LV3}} - \cdots \boldsymbol{E_{LVn}} \text{(Eq. 4)}$$

Here, let "n" is the number of zones (MV or LV)

However, the allocation presented here is independent of the loss calculation method, it is addressed toward the measurements of parameters on border elements around the network, lines and transformers. To do it, given the marked areas on the reference network, is enough to discriminate an outcomes analysis with scalarity.
All generators within a zone, topologically connected, will have the same loss coefficient value. The assigned value of losses will vary depending on the size of each unit. It is a novel conception for allocating of global losses in the system considering self-shared consumption by users.

Once the generation and demand curves are obtained, taking an account the model in figure 1, allocation coefficients are calculated from results of a quasi-static simulation, using the following equation along the sampling daily:

$$\boldsymbol{ALC_t} = \frac{[\Delta \boldsymbol{Losses}]_{\boldsymbol{t-1,t}}}{[\Delta(\boldsymbol{Pg_i} - \boldsymbol{Pd_i})]_{\boldsymbol{t-1,t}}} \quad \text{(Eq. 5)}$$

Where t denotes its value in moment of consumption or generation according to its time-series.
$(Pg_i - Pd_i)$: Total power supply from network or surpluses to network.
Losses= Total assignable losses (From simulation).
Pgi = PV generation injected to network; *Pdi*= demanded power.

In order to adjust a normalization process, the total losses would be:

$$\boldsymbol{Lt} = \boldsymbol{ALC} * \left(\boldsymbol{Pg_i} + \boldsymbol{Pd_i}\right) * \boldsymbol{K_0} \quad \text{(Eq. 6)}$$

Where:

$$\boldsymbol{K_0} = \frac{\boldsymbol{Total\ losses\ (in\ LV\ or\ MV)}}{\boldsymbol{Lgi} + \boldsymbol{Ldi}}$$

Lgi= Allocated losses to generation by zone
Ldi= Allocated losses to demand by zone

4.1. Technical modelling: quasi-static simulation

Through phasor measurement at load and generation on the modelled network using Simulink/Matlab, a database of solar radiation and typical demand of a user is entered as input of the proposed procedure.
In this application, the loss allocation procedure was applied for a distribution system with 2 feeders.

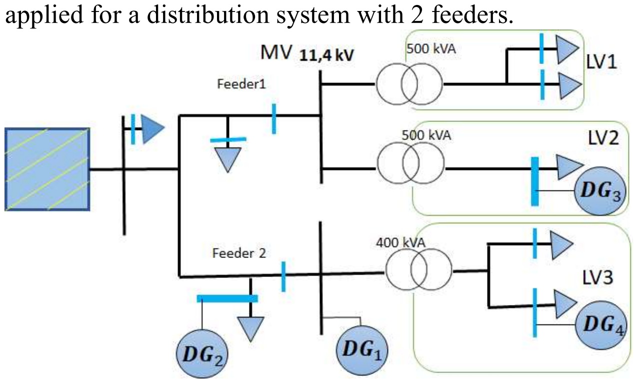


Figure 2. Radial network for MV and LV. Based in [23]

A quasi-static simulation was realized on a typical network of medium voltage (MV) and low voltage (LV). It consists of three transformers MV/LV (11, 4 /0,208 kV), with sizes 500 kVA, 500 kVA and 400 kVA respectively. Into the sampled measurement, 96 simulated data every 15 minutes throughout a typical day of energy consumption. This type of simulation allows to interactively simulate curves of load and generation inside the system through power flows on a radial feeder.
Demand is represented by aggregate concentrated loads, whose number of "n" users charged to the network, involve the characteristics of a user's daily consumption curve, according to Load Coincidence Calculations in [23] for MV and LV networks. Among the simulated cases a constant load was considered.

4.2. Shared Self-consumption

One of the major challenges to self-consumption (SC) in households is the disparities between power generation from PV and the actual demand [24]. This is the configuration of consumption when a user is able to consume energy from his DG and inject surpluses to the network, which case, it is called "shared".
In this study case of SC, DGs have been placed PV Solar, near and far a way of the transformer for zones LV2 and LV3. For MV, It was installed on at the head and end of the feeder 2.
For the scope of this case study, a demand measured curve for a residential user in Colombia will be taken into account, without storage. Therefore, the analysis focuses on the injection of surpluses into the network.
Below are the demand profiles by zone (base case):

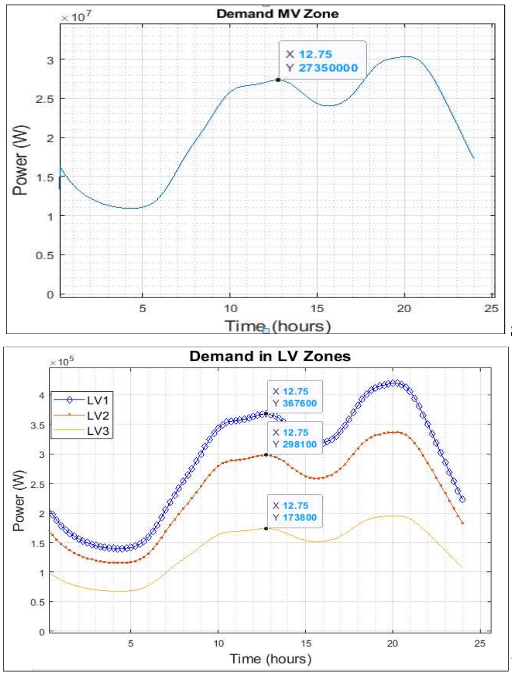


Figure 2. Demand profile by zones. a) MV b) LV

P_{peak} MV Zone = 27, 35 MW; P_{peak} LV1 Zone = 173,8kW; P_{peak} LV2 Zone= 298, 2 kW; P_{peak} LV3 Zone= 367, 6 kW

Zone LV1 does not have DG installed, although it is part of feeder 1, which has DG in LV2.

Summary step by step for loss allocation

1º-Construction or measurement of generation and demand curves. Interpolation or adjust time series.
2º-Choosing and modelling topology by zones
3º-Preparing the system – base case. To run quasi-static power flow.
4º-To review results in time series and to calculate coefficients.
5º. To repeat 3º and 4º for PV solar injection. By last, to redistribute losses according to allocation on demand and generation.

5. Results and discussion

The PV deployments used in the analysis are selected from the steady-state analysis results based on monitoring criteria of the impact [21]. The aims of the time series analysis include [11]:

i) From the actual load and solar data, to determine feeder response. ii) Comparison between the steady-state analysis and time-series response. iii) To examine the PV Solar DG on control elements. Clearly, the time-series analysis is conducted for load/PV time-of-day coincident scenarios.

Changes in the load level can be better coordinated using a mode schedule based on the time of day, which can also benefit the reduction of losses, for example, in light loading periods by changing control modes [10].

For the analysis, it is established to refer as penetration level, similar to [16], which is defined as:

$$\boldsymbol{PL_{PV} = \sum_{i=1}^{n} P_{gi}/P_d} \qquad \text{(Eq. 7)}$$

Where: Pg= Peak power of solar PV plant in zone

Pd= Peak power demanded at consumption

It is not contemplated in the scope of this paper, when the penetration level is greater than 1, for each zone of distribution, as suggested in [16] on the need to storage in water pumping or import of power from the transmission system.

Below is a graph with results of total losses for simulated Cases: $PL_{PV} = 0$ is the base case (BC). C1: $PL_{PV} = 0.25$, $C2$: $PL_{PV} = 0{,}5$, $C3$: $PL_{PV} = 0{,}75$ and $C4$: $PL_{PV} = 1$, C1 to C4 are cases with DG). The penetration level is indicated on the figure 3:

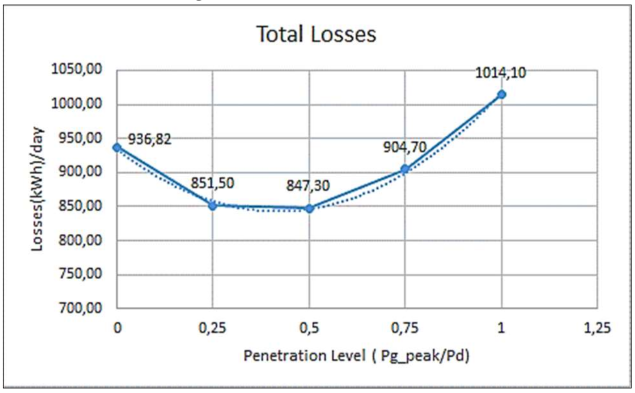


Figure 3 Total losses by case

As can be observed for case 3, reaching 904.7 kWh of losses, losses have increased with respect to case 2, but still remain below the base case. The last case is extreme and was performed optionally to evaluate system behavior.

A. Relationship between surpluses and energy losses

From the present analysis, when a consumption zone is analyzed, the curve $(\sum \boldsymbol{P_g} - \sum \boldsymbol{P_d})$ would approximate a total value of losses throughout the zone. Downstream, if it is calculated perform a curve $(\boldsymbol{P_g} - \boldsymbol{P_d})$ at point of common coupling (PCC), then resulting variable are network power surpluses. This remark is important to establish the sense of power flows on lines. Therefore, to quantify the ratio between energy losses and surpluses injected from GD, a correlation of Pearson was used.

In terms of power balance in figure 4, $\boldsymbol{P_g}$ corresponds to power generated to shared SC node, $\boldsymbol{P_d}$ is demand power and $\boldsymbol{P_{grid}}$ corresponds to the power supplied by the network from STR. In order to illustrate that occurs with the shared consumption on DG injection nodes, the following figure 4 is shown:

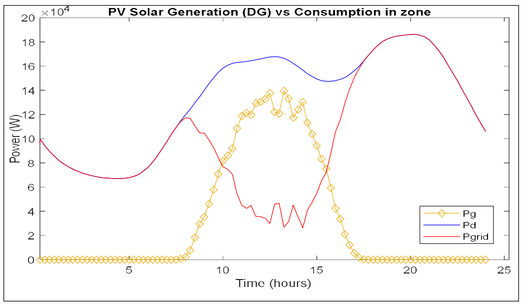


Figure 4. Power balance in zone with DG Solar PV

For the case study, it is performed for the interval (from 6 until 18 approx.), to address the peak of full solar generation during the day. The Pearson's correlation for the simulated cases is presented below in figure 5:

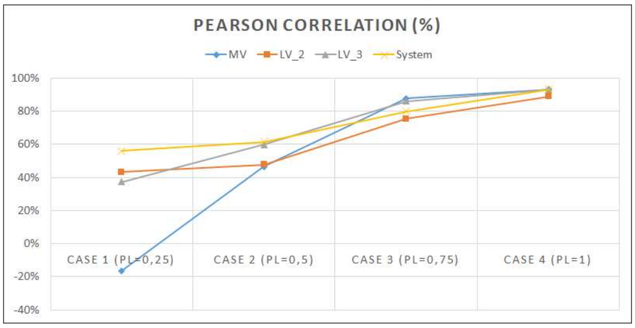
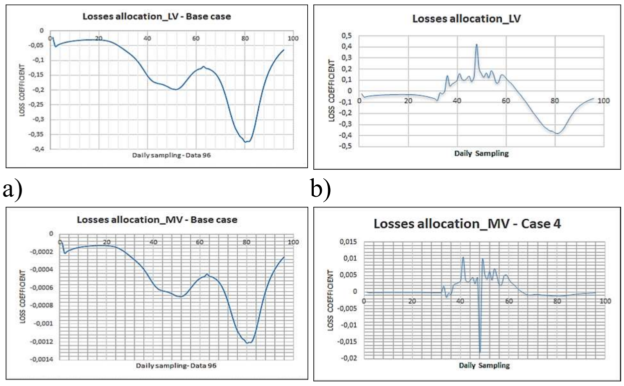


Figure 5. Person´s correlation. Power injection vs Losses

It can be concluded that for low penetration levels of DG, the correlation is not significant between the injection of power to the grid and the losses per zone. An initially negative correlation for medium voltage indicates that the quantified variables are inversely related. As expected for cases 3 and 4, the correlation amounts to 80% and 93% respectively, for the complete system. Something similar occurs in medium voltage and low voltage, a symptom of overcoming the hosting capability of power for circuits in mention.

B. Curves of allocation Coefficients

Figures 6 a) and b) show a curve of loss coefficients for a low voltage network. A base case corresponds with a scenario without connected distributed generation. For medium voltage level, the coefficients are smaller than in LV, with order 10^{-2} as shown in Figure 6 with PV solar DG. It is compared against a scenario with high penetration of photovoltaic solar (Case 4) power and it is possible to observe variation of the loss coefficient for each case.
With regard to this analysis, it could be said that the evident behavior of the coefficients shows better signs of loss reduction during the day. Because of the allocation, in each scenario are allocated lower losses, before exceeding its hosting capacity by this factor.



a) b) c) d)

Figure 6. Curves of allocation coefficient. **a, c)** Without PV Solar (BC) for LV and MV respectively; **b, d)** With PV Solar (C4) for LV and MV.

Given the results, the losses allocation coefficients emerge as a useful application tool in real time, based in [15], through which it is possible to detect technical phenomena into network operation with DG plants, aspects such as: load changes, variation of global losses and plants entry.

Its polarity is determined due to the amount of supply via surpluses toward network. Besides, within the technical impact, this analysis represents an approximation signal to assess power hosting capacity from losses limits of the system with certain penetration levels of DG [8].
The application of assignment coefficients is flexible and useful because it arises as a proposal similar to a system per unity, able to store information on total losses of a system, weighting its normalization on power size or energy (demanded by load or injected by generator) of each responsible.

C. Allocated losses via regulation

The allocated losses for this procedure are:

Zones	BC	C1	C2	C3	C4
LV1	7,02	6,84	6,72	6,64	6,58
LV2	5,18	4,57	4,50	4,8	5,45
LV3	3,67	3,08	3,2	3,70	4,61
MV	0,18	0,16	0,16	0,8	0,2

Table 1. % Efficient Losses by allocation

All allocation percentages estimated by the procedure are lower than the national average index of recognized losses, the difference in average value being greater than 88% for MV (level II) and 46% for LV(Level I) zone for the analyzed cases.
When redistributing losses for generation and demand, table 2 shows percentage results for everyone:

Zones	C1		C2		C3		C4	
	L_G	L_D	L_G	L_D	L_G	L_D	L_G	L_D
LV1	0	100	0	100	0	100	0	100
LV2	5,4	94,6	9,2	90,8	14,2	85,8	20,6	79.4
LV3	4,99	95,01	9,4	90,6	16,8	83,2	25,6	74,4
MV	2	98	5.1	94.9	12,6	87,4	21.1	78,9

Table 2. Allocated losses percentages between DG and demand

As a result, it is possible to infer that as the penetration rate increases, the responsibility increases significantly between generation and demand, which is consistent with what is related in Pearson's correlation. Within a regulatory framework, its application interpretation must contemplate the curve presented in Figure 3, as to whether there is an increase or not, with respect to a base case. This latter would not necessarily should be one immediately prior to the topological state of the network, as it would be a misinterpretation, as has been demonstrated between cases 2 and 3 where there are rising in losses, both of which are still beneficial to the system. In addition, between cases 3 and 4, without doubt, there is a general increase in losses, and as observed in allocation table, responsibilities increased for all participants within allocation by zone.
On the other hand, losses are significant in magnitude for low voltage areas. It is striking that from case 3, which corresponds to an approximate penetration peak of 75%, assigned percentages of losses increase. This is consistent with the general increment in losses after this scenario.
In addition, LV zone 1, despite not having DG connected, sees a marginal reduction of losses of 0.44% from the base case to case 4, due to the losses impact on the feeder that has DG connected in LV2 zone.

6. Conclusion

In this paper, an analytical procedure has been developed that allocates losses in time series by voltage zones through the demand and generation curves with self-consumption. The theory has been exemplified in case of high penetration of PV solar energy means 4 cases of incremental step , within a quasi-static power flow, sampled every 15 minutes.
The allocations are made involving sensitivity to power injections to the network, and alerting the raising correlation between these and power losses.
The configuration of self-consumption for modelling requires separating losses and demand from its measurement and simulation. This is achieved on injection node, tracking the direction of radial power flow.
On the other hand, it is valid to mention that the optimal operation of the system goes through the coexistence of DG and network, monitoring parameters of technical impact as losses. In this way, it is possible to evaluate a range of power hosting capacity in order to maintain an operational criteria on the distribution network, without detriment of opportunity to access for new users of PV Solar, and this certainly it represents a sign of economic efficiency into the regulatory framework.

Acknowledgements*:* Authors wish to acknowledge Messrs. Miguel Ángel Zorrozua, José Félix Miñambres, and German Corredor for useful suggestions and discussions about this important topic for the energy transition, as well as from the GISEL research group of the UPV/EHU.

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