Assessment of Energy Distribution Losses for Increasing Penetration of Distributed Generation

Víctor H. Méndez Quezada, Juan Rivier Abbad, *Member, IEEE*, and Tomás Gómez San Román, *Member, IEEE*

***Abstract*—High levels of penetration of distributed generation (DG) are a new challenge for traditional electric power systems. Power injections from DGs change network power flows modifying energy losses. Although it is considered that DG reduce losses, this paper shows that this is not always true. This paper presents an approach to compute annual energy losses variations when different penetration and concentration levels of DG are connected to a distribution network. In addition, the impact on losses of different DG technologies, such as combined heat and power, wind power, photovoltaic, and fuel-cells, is analyzed. Results show that energy losses variation, as a function of the DG penetration level, presents a characteristic U-shape trajectory. Moreover, when DG units are more dispersed along network feeders, higher losses reduction can be expected. Regarding DG technologies, it should be noted that wind power is the one that shows the worst behavior in losses reduction. Finally, DG units with reactive power control provide a better network voltage profile and lower losses.**

***Index Terms*—Distributed generation (DG), distribution, losses.**

I. INTRODUCTION

ELECTRICAL power systems are evolving from the nowadays centralized bulk system, with generation plants connected to the transmission network, to a future more decentralized system, with smaller generating units connected directly to distribution networks near demand consumption. This type of generating unit is known as distributed generation (DG) [1]. Various reasons are at the core of these changes. Environmental consciousness and sustainable development based on long-term diversification of energy sources are key aspects on the agenda of energy policy-makers. This has contributed to the promotion of renewable energy sources and combined heat and power (CHP) generation. On the other hand, a major breakthrough in high-efficiency small generators and natural gas availability are allowing for the development of micro-turbines and fuel-cells.

Power injections from DG change magnitude and even direction of network power flows. This causes an impact on network operation and planning practices of distribution companies with both technical and economic implications [2]–[7]. For instance, from the point of view of supply security, DG connection involves reviewing the design and adjustment of system protection devices; from the point of view of network operation, voltage profiles, energy losses, and maintenance and system restoration practices, in case of faults, are also affected [2]–[5]; and finally from the point of view of network design and planning, network reinforcement and additions should take into account future DG installations [6], [7].

Despite the aforementioned technical and economic implications of DG, the presented research has been concentrated on the evaluation of energy losses variation as a function of the main parameters that characterize DG connection to distribution networks. In addition, several regulatory implications associated to this impact are also identified.

The connection of DG to radial distribution networks can change power flows from unidirectional to bidirectional affecting load-related losses. Neither no-load losses nor nontechnical or commercial losses depend on power flows; therefore, they are not considered in this paper.

From the regulatory point of view, distribution companies' regulation is affected precisely by the issue that is analyzed in this paper. In general, distribution companies (DISCOs) have an economic incentive to reduce losses in their networks. Usually, this incentive is the cost difference between real and standard losses. Therefore, if real losses are higher than standard ones, the DISCOs are economically penalized, or, if the opposite happens, they obtain a profit. An example of this incentive mechanism is the one applied in Spain, through the following mechanism: in the wholesale market, DISCOs buy the energy losses that are consumed in their networks obtained as the difference between the injected energy into their networks less the sold energy to final costumers. On the other hand, consumers pay the DISCOs the energy they consume times a standard loss coefficient, which is set for a regulatory period of several years. This means that the DISCOs buy real losses, but they receive payments for an amount of standard losses [8].

Since the installation of DG will impact on distribution losses, it will have a direct consequence on the DISCOs' profit. If DGs decrease actual network losses, the DISCOs' profit will increase, but if the opposite happens, the DISCO's benefits will decrease. With the purpose to transfer the losses impact to the agents in the system (DISCOs, customers, and DGs) in the following regulatory period, it is necessary to calculate new standard loss coefficients for demands and generators.

Several studies have been conducted to assess losses variations and/or to allocate such variations between DG and consumers. Reference [9] did pinpoint the importance of losses variations for DG connection costs and proposed a methodology, based on second-order sensitivities, to compute such losses variations. However, this method is only valid for small DG penetration variations, as it will be proved later in this paper. References [10] and [11] proposed different methods to compute marginal nodal losses in order to provide economical signals to both consumers and DG. Reference [12] made the

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The authors are with the Instituto de Investigación Tecnológica, Universidad Pontificia Comillas de Madrid, 28015 Madrid, Spain (e-mail: tomas.gomez@iit.upco.es).

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analysis of predicting how losses will vary when connecting a specific photovoltaic plant to a specific feeder, based on a feeder section-by-section analysis. Other authors analyzed some other aspects, as the importance of the location of DG for losses reduction [13]–[15], even proposing in some cases some optimization algorithm to find the better DG location. How the control of the reactive power injected by DG plants impact losses levels was studied in [16] and [17]. A more complete study was carried out in [18], where impact of operational aspects on losses variations and acceptable DG penetration levels are analyzed, based on a specific case study.

DG impact on losses is an aspect of great interest, as shown by the number of different studies performed on this subject. Most of these studies have concentrated on studying a specific case (feeder and DG plant connection) or to develop a methodology to assess specific losses situation when a particular scenario of DG penetration has been analyzed. There is a lack of knowledge on what is the expected evolution of losses in a feeder, as a function of different parameters, such as DG penetration, DG technologies mix, DG dispersion and location, or reactive power control strategy.

This paper covers such a knowledge gap, through the analysis of the impact of DG on distribution losses by studying different scenarios with several DG penetration and concentration levels. Losses are evaluated on an annual basis. Different DG technologies, such as CHP, wind power, and photovoltaic cells, are modeled. For each type of technology, different penetration levels, corresponding with different amounts of DG installed capacity, and different concentration levels, corresponding with several DG units connected along the feeder, are studied.

This paper continues and completes the preliminary research presented by the same authors in [19], improving modeling issues and confirming previous results. The structure of this paper is as follows. Section II presents the adopted general approach and proposes some term definitions that are used later. Section III details modeling issues such as the network model, the hourly energy production for each type of DG technology model, and the location of DG units along the network to simulate different concentration levels. Computational algorithms are described in Section IV. Finally, results and conclusions are presented in Sections V and VI, respectively.

II. General Approach

The developed approach computes annual losses in a distribution network where DG units have been connected. Therefore, losses should be calculated for every hour of the year. This requires to run a load flow for each hour, taking into account load demands and DG productions at that hour.

To analyze the overall impact of DG on losses, several scenarios with different DG technologies, penetration, and concentration levels were created. DG impact on losses was measured as the difference between losses in the considered scenario and losses in the base case (without DG). Finally, the results obtained are presented through different types of curves that show how network losses change versus DG penetration and concentration levels for each type of DG technology.

A. Definitions

Some useful definitions used in this paper are as follows.

- *DG production*: Energy produced by DG units connected to a distribution network. It changes every hour of the year.
- *DG installed capacity*: The total maximum output of each DG unit. The DG installed capacity in the network is the sum of the individual DG installed capacities.
- *Capacity factor*: The ratio of the energy produced, during the period of time considered, to the energy that could have been produced if DG would have operated at continuous full power during the same time period.
- *DG penetration*: The ratio of the amount of DG energy injected into the network to the feeder capacity

$$\text{DG penetration} = \frac{\text{capacity factor} \times \text{DG installed capacity}}{\text{feeder capacity}}. \quad (1)$$

- *DG concentration*: Degree of concentration of DG units along the network feeder. It is measured as a function of the number of nodes with DG versus the total number of feeder load nodes. All DG units connected to a few nodes or even to a single node mean a high concentration level. On the contrary, DG units connected to several nodes mean a low concentration level.
- *DG mix*: A mixture of DG technologies that have been connected into the feeder. For instance, a "Mix CHP50-WT50" is a scenario with the same installed capacity in CHP units as in wind turbines (50% of CHP and 50% of wind turbines).
- *Annual energy losses (%)*: The ratio of total energy losses to the total energy demanded in the feeder on an annual basis.

III. Modeling

A. Network Model

In this paper, different medium-voltage radial distribution networks have been analyzed, obtaining in all the cases similar qualitative results. In order to better illustrate the methodology and the influence of every DG parameter, only the results of the radial IEEE 34-node test feeder (see Fig. 1 and Table I) are presented in this paper. Detailed information about this feeder can be found in [20].

B. DG Units Modeling

The effect of DG on losses depends on the number and size of DG units and their energy production patterns. DG units are characterized according to their constructive technology and their reactive power control scheme.

1) DG Technologies: Hourly energy production for each DG unit, during a whole year, has been modeled according to the specific DG technology characteristics.

- *CHP units*: These units were simulated by an hourly generation profile obtained from recorded real annual hourly data from a set of CHP plants. First, a typical generation profile was obtained for the whole set of

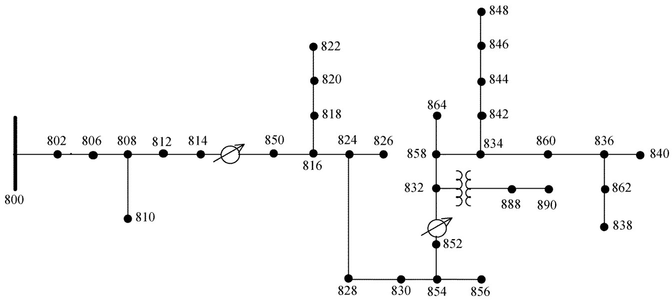

Fig. 1. Single-line diagram of the IEEE 34-node test feeder.

TABLE I
BASIC DATA OF THE IEEE 34-NODE TEST FEEDER

Voltage	24,9 kV
Feeder Capacity	713,1 kVA
Length	93,9 km

CHP units. Then, individual energy productions were obtained by modifying the typical generation profile with a superposed random noise that represented observed hourly differences from plant to plant. This randomness was introduced by a uniformly distributed noise for every hourly data. This noise was set at ±25% of the basic generation profile.

- *Wind turbines*: These DG plants were simulated using the Markov matrix simulation method described in [21]–[23]. For each wind turbine, this method correlates the energy production in the present hour with the energy production in the previous hour. This correlation matrix was calculated using real hourly wind farm production data.

  A wind farm was simulated as a single wind power unit with installed capacity equal to the total wind farm capacity.
- *Photovoltaic*: In order to model this kind of unit, the hourly variation of solar radiation was simulated. This variation is due to the passage and rotation movements of the earth throughout the year. The model used the geographical coordinates of the power plant to compute theoretical values of extraterrestrial radiation. The radiation that reached the terrestrial surface was estimated using local correction factors to take into account the effect of clouds.

  The power produced by photovoltaic units was estimated using the characteristics provided by the manufacturers of solar cell arrays, taking into account hourly values for the calculated radiation.

  In order to represent typical hourly differences from plant to plant, the local correction factors of each plant were modeled through two uniformly distributed random numbers: one for the monthly local correction factor (set at ±20% of the base value) and the other one for the daily local correction factor (set at ±50% of the base value).
- *Base-load generation*: This is a generic type of DG technology that was used to model DG units that can produce full power almost during the whole year, such as fuel-cells or micro-turbines working as base load plants.

2) Control of Reactive Power: An important issue regarding the impact of DG on power losses is the capability of DG to control voltages and to provide reactive power support.

The capability of DG to supply reactive power depends on its generator technology. Some DG technologies cannot control reactive power, for instance, traditional wind farms based on asynchronous generators. Other DG technologies are able to control reactive power, although due to regulatory or economic reasons, they are not encouraged to do so. For instance, CHP plants with synchronous generators are able to provide reactive power support. DG technologies with power electronic interface based on self-commutated converters, IGBT devices, can be operated at any desired power factor [2]. Examples of this type of DG are photovoltaic, wind turbines, micro-turbines, fuel cell, etc., with all of them connected to the network through ac-dc converters.

Traditionally, DG has been considered as not having the capability to control voltages, and therefore, it has been modeled in power flow studies as a negative load, i.e., as a PQ node. However, if DG is able to control reactive power, the node where DG is connected should be modeled as a PV node. This represents the DG generator capability to keep a voltage reference value while the supplied reactive power is within its maximum and minimum limits.

C. Load Modeling

The computation of energy losses on an hourly basis requires the knowledge of hourly energy consumptions in each load node. The selected IEEE 34-node test feeder does not provide hourly load data. For this reason, the IEEE load data have been assumed as peak demands and demands for the rest of the year were obtained, assuming the same load evolution as real historical hourly data from Spanish consumers. Different combinations of types of consumers were assumed connected to each load node of this test feeder.

Load nodes were modeled as constant power sinks, i.e., independently of feeder voltage magnitudes.

D. Scenarios

To analyze the impact of DG penetration and concentration levels on energy losses, several DG scenarios were created. In each scenario, the DG penetration level was gradually increased from 0% (base case) to 15%.

Regarding DG concentration levels, the following scenarios were created.

- "Ideal" scenario: In this scenario, DG plants were installed in each load node. The DG installed capacity in each node was proportional to the load demand in that node.
- "Three DGs" scenario: In this scenario, three same-size DG plants were located strategically along the feeder to obtain a well-balanced load situation.
- "One DG" scenario: In this scenario, one single DG plant was located alternatively in different nodes along the feeder.

Regarding DG generation mix, several scenarios have been modeled to represent the different types of generation technologies connected to the same feeder node. For instance, a scenario denominated "Mix CHP50-WT50" represents a DG plant with the same installed capacity in CHP units as in wind turbines (50% of CHP and 50% of wind turbines).

IV. Computational Algorithms

In order to compute energy losses on an annual basis, a load flow algorithm should be run each hour of the year. Annual losses are calculated as the sum of hourly energy losses. In addition, in this paper, many different scenarios, each one meaning a whole year simulation, were analyzed. Therefore, several load flow algorithms were compared in accuracy and speed with the purpose to select the one with a better performance.

The Newton–Raphson (N–R) algorithm was taken as a reference for the purpose of comparison.

A. Load Flow Algorithms

1) N–R Load Flow: This is the more precise algorithm but it requires a high computational burden since it is necessary to calculate the inverse of the Jacobian matrix in each iteration.

2) Radial Load Flow: Many radial load flow algorithms have been mentioned in the literature [24]–[27]. These algorithms take advantage of the radial or arborescent structure of distribution networks. These types of algorithms are also iterative, but they do not require the inversion of any matrix and, therefore, are faster than N–R algorithms. This aspect becomes more relevant as the size of the distribution network increases. Unfortunately, these types of algorithms only allow for a representation of PQ load nodes; therefore, DG reactive power control capability cannot be analyzed.

The results presented in this paper in Figs. 2 and 3 were obtained with a radial load flow algorithm similar to the one in [24].

3) Second-Order Sensitivities: These types of algorithms are based on a second-order Taylor approximation of total active power losses. Disturbance variables are defined as the net generation of active and reactive power in each PQ node. Therefore, DG has to be modeled as a negative load. In this research, the load flow for the base case without DG in each hour of the year was taken as reference. Then, losses for each hour and different scenarios were estimated with second-order sensitivities.

The results presented in this paper in Fig. 2 were obtained with an algorithm similar to the one described in [9].

4) Losses in Time-of-Use (TOU) Periods: A simpler way to estimate annual losses is to compute the losses in a few representative hours of the year instead of in each single hour. This option can be implemented with any of the previous load flow algorithms. In this research, this option has only been combined with the most precise algorithm, i.e., Newton–Raphson. The presented results in Figs. 2 and 3 represent the loss of accuracy due to the use of this simple method.

In particular, the year was divided into six time periods based on the Spanish TOU tariffs [28]. The average load for each load node and the average generation for each DG plant were calculated for each TOU period. Using these average values, the average losses for each period were calculated through a run of the N–R load flow algorithm. Annual losses were calculated by the weighted sum of TOU losses.

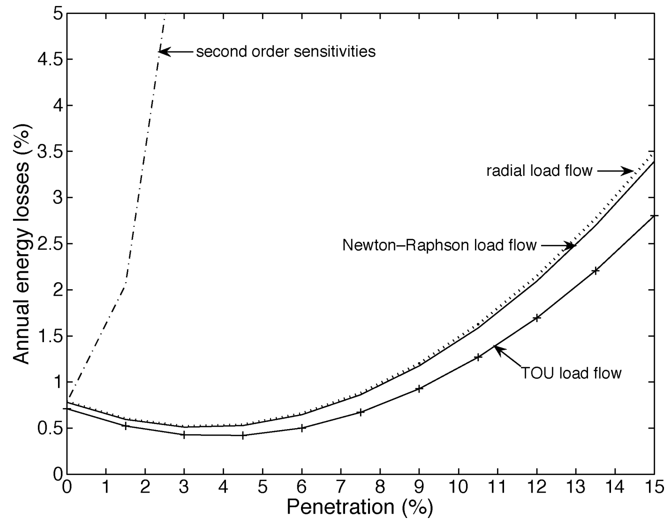

Fig. 2. Comparison of load flow algorithms.

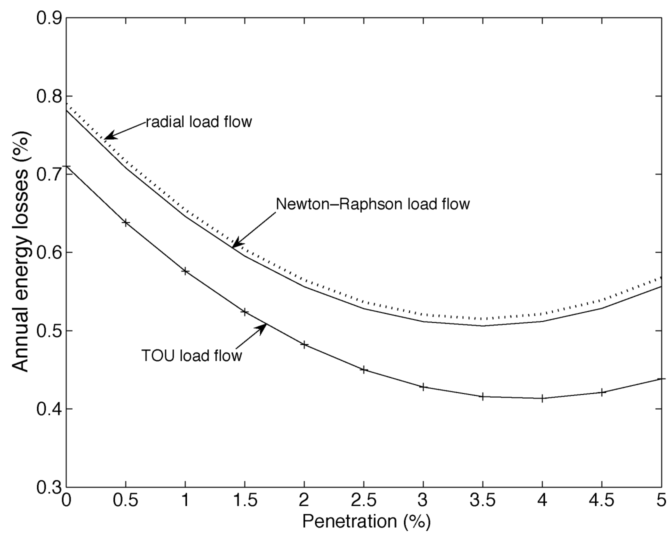

Fig. 3. Enlargement of Fig. 2.

B. Evaluation of Algorithms

Figs. 2 and 3 show the results obtained in the "ideal" concentration scenario with CHP DG units. As can be observed, the second-order sensitivities algorithm should be rejected due to the inaccuracy of the provided results. As DG penetration levels increase, disturbance variables are not valid for estimating losses based on second-order sensitivities.

The accuracy of the results obtained with the radial load flow algorithm is excellent. In addition, in this case, there were no significant differences in the computational burden with the N-R algorithm because the considered feeder was small enough. In conclusion, radial load flow would be preferred in the case of larger networks and assuming there is no need to analyze DG reactive power control capabilities.

Finally, the computation of annual losses in TOU periods provides accurate results if DG penetration levels are low enough. The losses estimation error increases with the DG penetration level.

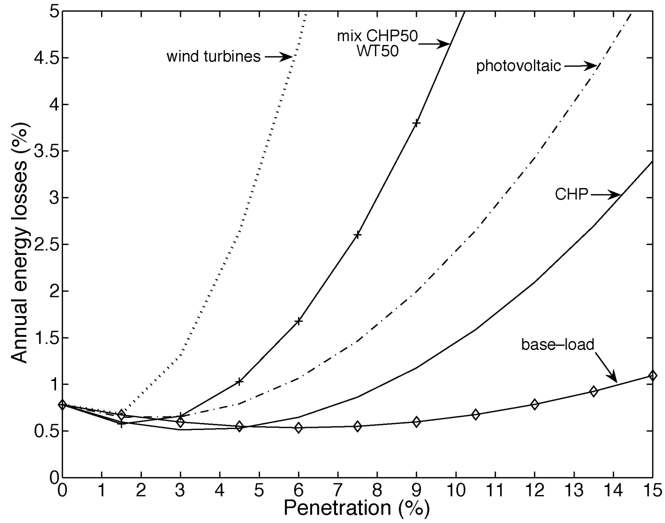

Fig. 4. Annual energy losses ("ideal" scenario).

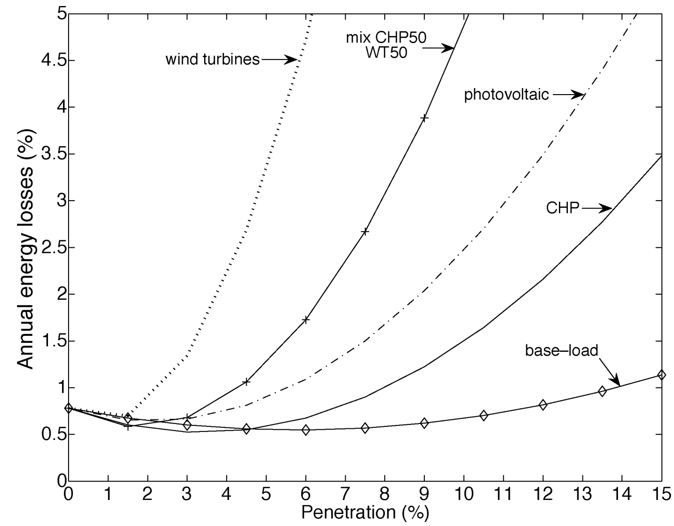

Fig. 5. Annual energy losses ("three DGs" scenario).

V. Results

In this section, different results are presented that were obtained by applying the developed approach to evaluate energy losses variations when DG is connected to distribution networks.

A. Energy Losses Versus DG Production

In order to analyze the impact of DG energy production on energy losses, DG was modeled as a negative PQ load with a power factor equal to one.

Fig. 4 shows the evolution of losses in the "ideal" scenario for different DG technologies. The first result that claims attention is the shape of all the traces. Losses start to decrease when connecting small amounts of DG until they reach their minimum level. Once this minimum level is reached, if DG penetration level still increases, then losses begin to marginally increase too. If DG penetration levels increase enough, then losses can be even higher than without DG connected (more than 5 times in extreme cases). This type of shape has appeared in all the studied cases.

Regarding the impact of each DG type of technology, it can be observed that wind turbines have the least positive impact on losses, because the injected energy is intermittent, presenting high time variability, and does not match well with the feeder load pattern. As expected, the mix CHP50-WT50 shows a performance in between CHP and wind turbines technologies.

The impact on losses of the rest of the technologies is also explained by the expected matching between hourly energy generation and hourly load demand patterns.

Similar performances were observed in all the different types of networks that were simulated.

Fig. 5 shows the results for the "three DGs" scenario with DG connected in nodes 826, 848, and 838. In this scenario, losses are quite similar to those in the "ideal" scenario. This result shows that three well-chosen nodes to locate DG plants produce identical benefits to that of an ideal DG location.

Fig. 6 shows the results for the "one DG" scenario with a DG plant connected in node 848. As can be expected, in this situation losses are higher than in the above-mentioned cases.

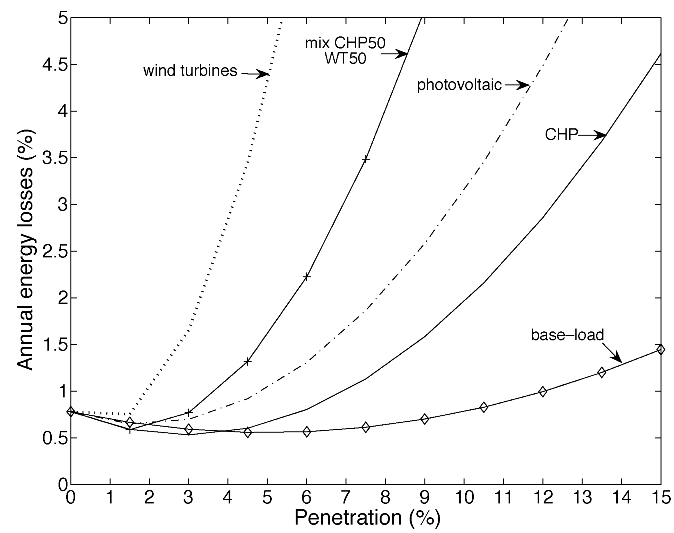

Fig. 6. Annual energy losses ("one DG" scenario).

TABLE II
Capacity Factor of Each Technology

CHP	0.5
Wind	0.25
Photovoltaic	0.125
Base-load	1.0

Understanding the previous results, it is important to emphasize the effect of the capacity factor of each DG technology. Due to the adopted definition of DG penetration level (see Section II-A), a DG technology with a low capacity factor represents, for the same level of penetration, much more DG capacity installed than a DG technology with a higher capacity factor. The capacity factor of each technology is presented in Table II.

In addition, the DISCOs or DG connection standards can limit the maximum DG capacity allowed along a distribution feeder or connected to a distribution transformer. For instance, in Spain, the maximum DG installed capacity in a distribution feeder should be kept lower than 50% of the maximum feeder capacity. In our case study, assuming a maximum feeder capacity of 713 kVA, the maximum DG installed capacity should

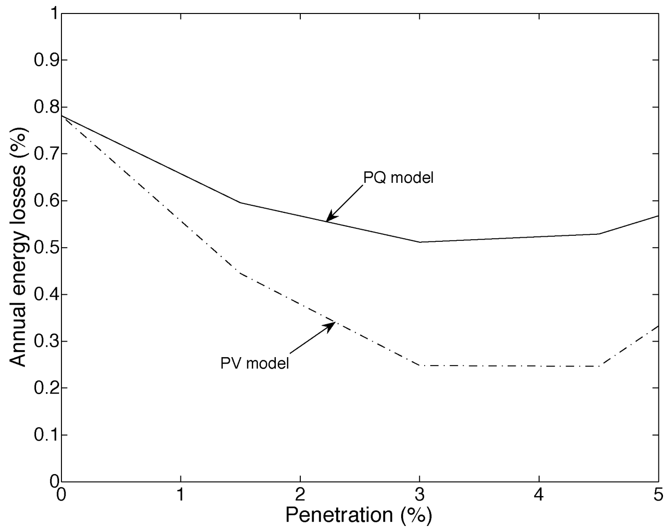

Fig. 7. Comparison of DG modeling (PQ or PV). CHP "ideal" scenario.

be 356.5 kVA, which would correspond with a penetration level of 12.5% if wind turbines were installed (capacity factor $=$ 0.25) or with a penetration level of 6.25% if photovoltaic plants were installed (capacity factor $= 0.125$). Therefore, it is important to keep in mind that when applying the results obtained in this study, the validity range of the energy losses variation curves changes from one DG technology to the other. For instance, for photovoltaic units, penetration levels only range from 0 to 6.25%, while for wind plants, they range from 0 to 12.5%.

B. Energy Losses Versus DG Reactive Power Control

Fig. 7 shows a comparison of energy losses variations under two different reactive power control situations. First, DG is assumed working each hour with a constant power factor equal to one. In this situation, DG is modeled as a PQ node (PQ model). Second, DG is assumed providing voltage control and reactive power support. DG is modeled as a PV node maintaining each hour a voltage equal to a reference value set by the distribution system operator (PV model). This reference voltage was selected equal to the voltage in the base case (without DG) plus 5%. The maximum reactive power that DG can supply or consume was set at a power factor equal to 0.8.

As can be seen in Fig. 7, voltage control made by DG units decreases energy losses because reactive power flows along the feeder are better controlled. These figures have been obtained without optimizing the reactive or voltage control, just using a fixed voltage reference. This means that it is possible to design better voltage control strategies that would be able to obtain much better results.

Another control strategy, even less sophisticated than the one previously presented, could be to set different power factors that should be kept by DG units in different time periods. This is the strategy that has been followed in Spain, where renewable and CHP DG units are encouraged to supply reactive power during peak hours and to consume reactive power during off-peak hours. A bonus is set as a percentage of the premium that this type of generation receives associated with energy sales, as is shown in Table III.

TABLE III
INCENTIVE TO SUPPLY OR TO CONSUME REACTIVE POWER FOR RENEWABLE AND CHP GENERATION IN SPAIN

	$\cos\phi$	Bonus (%) Peak hours	Flat hours	Valley hours
Lagging	$\cos\phi < 0{,}95$	-4	-4	8
	$0{,}95 \le \cos\phi < 0{,}96$	-3	0	6
	$0{,}96 \le \cos\phi < 0{,}97$	-2	0	4
	$0{,}97 \le \cos\phi < 0{,}98$	-1	0	2
	$0{,}98 \le \cos\phi < 1$	0	2	0
	$\cos\phi = 1$	0	4	0
Leading	$0{,}98 \le \cos\phi < 1$	0	2	0
	$0{,}97 \le \cos\phi < 0{,}98$	2	0	-1
	$0{,}96 \le \cos\phi < 0{,}97$	4	0	-2
	$0{,}95 \le \cos\phi < 0{,}96$	6	0	-3
	$\cos\phi < 0{,}95$	8	-4	-4

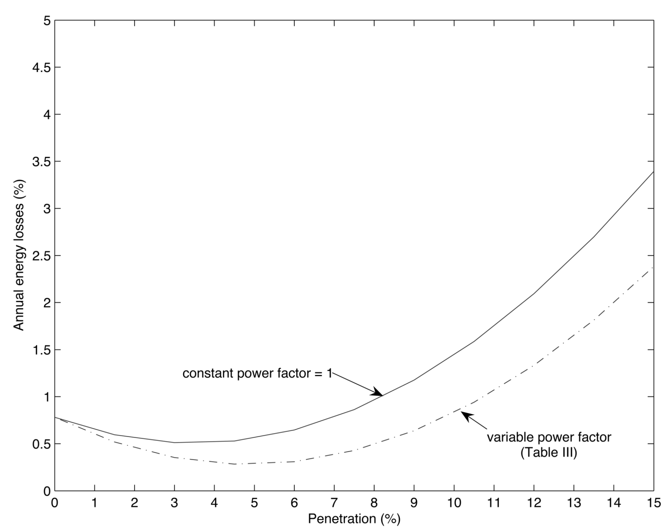

Fig. 8. Comparison between a constant power factor and a variable power factor with time discrimination control strategies. CHP "ideal" scenario.

Fig. 8 shows the benefits in energy losses associated with the aforementioned reactive power control strategy versus keeping a constant power factor equal to one. It is clear that to supply reactive power during peak hours or to consume it during off-peak hours has a beneficial effect on voltages and losses. This simple rule can have some exceptions that would be overcome if the most sophisticated real-time control strategy would be implemented. A regulatory recommendation could be that large DG generators should implement the real-time voltage control strategy, while medium and small DG generators would perform adequately if the time period power factor control strategy were adopted.

VI. Conclusion

In this paper, the impact of DG on distribution losses has been analyzed. Several DG technologies and DG penetration and concentration levels along the feeder have been studied.

The main contribution of this paper is the qualitative results, which can be applied to most situations. The results presented help to understand the influence of each parameter that affect annual losses variations: mainly DG penetration but also technology mix, dispersion, location, and reactive power control.

In all the situations, annual energy losses variation as a function of the penetration level of DG shows a U-shape trajectory. Losses start to decrease with low DG penetration levels, whereas after a minimum value, they start to increase with higher DG penetration levels.

DG concentration along the feeder also impacts on energy losses variations. The more dispersed the DG units are, the greater the impact is on losses. However, results show that in most feeders, three DG units strategically connected are enough to produce the same benefit as an ideal situation with multiple dispersed DG units.

Wind turbines have a less positive impact on losses than other DG technologies, as for instance, photovoltaic units. Intermittent and random energy injected by wind turbines does not match well with feeder load patterns. On the contrary, photovoltaic production follows better daily load variations.

Control of reactive power supplied or consumed by DG also impacts on energy losses. The more sophisticated the voltage and reactive power control strategy is, the greater the impact is on losses. Large DG generators should control voltages in real time. Medium and small generators can keep a constant power factor with time discrimination. In a competitive framework, DG units should receive suitable economic signals to encourage them to control reactive power.

The numerical results presented in this paper correspond with a specific case study. Other distribution networks with different topologies and load patterns have been also analyzed by the authors, obtaining similar qualitative results but with important numerical differences regarding energy losses values.

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Víctor H. Méndez Quezada was born in El Salvador. He received the Electrical Engineer degree from the Universidad de El Salvador, San Salvador, in 1998. Currently, he is working toward the Ph.D degree at the Instituto de Investigación Tecnológica (IIT), Madrid, Spain.

He is a Research Assistant at IIT. His areas of interest are distributed generation, regulation, and economy of electric energy systems.

Juan Rivier Abbad (M'99) received the Electronic Engineering and Ph.D. degrees from the Universidad Pontificia, Madrid, Spain, in 1992 and 1999, respectively.

He joined the Instituto de Investigación Tecnológica (IIT), Madrid, in 1992, where he is currently a Research Fellow. He has experience in industry joint research projects in the field of electric energy systems in collaboration with Spanish utilities. His areas of interest are regulation, operation and planning of distribution systems, power quality, and reliability issues.

Tomás Gómez San Román (M'88) received the Doctor Ingeniero Industrial degree from the Universidad Politécnica, Madrid, Spain, in 1989, and the Ingeniero Industrial degree in electrical engineering from the Universidad Pontificia Comillas (UPCO), Madrid, in 1982.

He joined the Instituto de Investigación Tecnológica (IIT-UPCo) in 1984, where he was Director from 1994–2000. From 2000–2002, he has been the Vice Chancellor of Research, Development, and Innovation at UPCO. He has a great deal of experience in industry joint research projects in the field of electric energy systems in collaboration with Spanish, Latino-American, and European utilities. His areas of interest are operation and planning of transmission and distribution electrical systems, power quality assessment and regulation, and economic and regulatory issues in the electrical power sector.