Distributed Generation and Demand Response Effects on the Distribution Network Planning

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***Abstract*—This paper studies the possible benefits/overcharges for a Distribution Network Operator (DNO) in the process of Planning the Distribution Network, when Distributed Generation (DG), and/or Demand Response (DR) policies are incorporated in the Distribution network. The results obtained for the design of the new grid with this participation are incorporated into the network planning process with different types of DG power plants and DR in their demand nodes, compared with the base case of demand obtained in the case of a network without changes in their consumption patterns neither DG incorporation. For the planning process of the new network in either cases, the classic Distribution Network Planning methodology was used, which is based on the classic economic theory of Minimum Total Cost (MTC) through which the Investment Plan of the Distribution Network of the Electrical Distribution Company is drawn up. The solutions obtained guarantee the supply of the power and energy demand of its customers at all times (all scenarios), minimizing the total cost equation and complying with the physical design constraints during the network planning horizon of 20 years. A genetic algorithm (GA) was used to search for the optimal solution (minim total cost) in a technical-economic point of view of the electricity network.**

***Keywords*—Distribution Network Planning, Distributed Generation, Demand Response, Technical Losses, Economic Evaluation.**

I. Introduction

Until now, electrical distribution networks have been designed and operated by the Distribution Network Operator (DNO), based that power always flows from the big substations to the final consumers on High Voltage, Medium Voltage and Low Voltage networks, and never produce inverse flows. But, recent industrial developments and deep changes in the electricity markets stimulate the fast growing of Distributed Generation (DG), and Demand Response (DR) policies. The operation of micro/macro-generation connected to the networks can cause overload on the feeder statutory voltage limits, voltage unbalance, levels violation, and switchgear fault ratings to be exceeded. However, the level at which this happens will depend upon the type of generator, the renewable energy font, and network characteristics.

In this context, the aim of this paper is to investigate and develop a proper methodology to evaluate long-term optimal network design strategies, and to determine the effect of the penetration of microgeneration and large scale DG and DR, on the Sub-Transmission (MV) Distribution Planning method.

The optimum design of the network is determined minimizing annual costs of equipment, its installation, operation, maintenance and technical losses, meeting all the technical and statutory constrains. The need for reinforcement of the network components will depend on the level of DG and DR penetration and on the extent to which reverse power flows happens. In most parts of the network, micro/macro reverse power flow result in any need for network investment/reinforcement. However, considering DG and DR at the moment of the distribution network planning, may change optimal design investment plan.

In this work the possible benefits/overcharges of incorporating DG and DR in a Distribution network are studied and compared. As a result of this, we show how this is reflected in the network planning process, and investment plans.

In the planning of the new network, a Sub-Transmission Network planning methodology is used, which is based on the classic economic theory of Minimum Total Cost (MTC) [3] through which the Distribution Plan of an Electricity Company is drawn up. For the economic evaluation the costs of: Investment, Operation & Maintenance and Technical losses are included, and with this information a cost function is generated which is intended to be minimized. Demand is also expected to grow for a time horizon of 20 years, for which the network must be able to supply the loads at all times.

To explore the set of possible solutions (combinations of feeders available to be installed in the network), a genetic algorithm is used by evaluating the cost function, subject to complying the constraints of the system. For the design of the network, we consider that it must be able to supply the demand at all times and especially at its peak consumption and for the entire 20-year planning horizon. The physical constraints of the network were included in the genetic algorithm as a barrier function that operates as a penalty within the function of cost evaluation. For the evaluation of the losses and to verify that the capacity of the feeders supports the maximum power consumed in each of the nodes, we use a load flow (power flow) that implements a Newton-Raphson method [2] [4] for the evaluation of the currents in each feeder, and the losses caused by supplying the demand.

Now that the network feeders have been chosen, we use the same real demand curve with load states for each hour of the year, modified by the insertion of DG and DR to determine how the losses of the system are affected with different technologies of DG and DR, and for different levels of penetration with respect to demand. We focus on the DG and DR policies that have had greater penetration in electricity markets such as wind and solar energy, and the most promising and scientifically motivated technologies to promote their development, such as the Combined Heat and Power (CHP), and Demand Response (DR).

Finally, we calculate again the cost of the original network but assuming the incorporation of DG and DR technologies, and for different levels of penetration meeting all the technical constraints, analysing the new costs and verifying whether the new choice of feeders improves the cost function and the previously calculated investment plan (we emphasize that at this point the investment cost of the DG and DR installation is not considered).

II. The Planning of the Distribution Network Methodology

A. Cost Minimization

The design and operation of the entire electric power system requires adequate planning to guarantee its operation at all times and ensure the planned expansion in the future. The distribution network planning process involves obtaining the program of future actions to be carried out in the network (10, 20 or 30 years), in order to achieve the proposed objectives while maintaining the proper functioning of the network at the lowest possible cost. The quality of supply must operate within limits required by the regulatory entity [1] and by the current legislation, example of this we can take the maximum and minimum levels of: voltage, frequency of the network, SAIDI, SAIFI, etc.

In general, the problem of network planning is a complex and non-linear problem that is based on optimization algorithms of a cost function that reflects the costs of the network (investment, losses and others costs associated with the quality of supply), subject to certain network constraints. Basically, the costs considered can be classified as follows:

- Investment costs (INV): corresponding to material, work-force, project realization, etc. It is considered that investments are made at the time of entry into service and that they are amortized over the entire useful life of the installation.
- Energy Loss Costs (LOSS): are those that occur throughout the period under study due to power losses in the different elements of the network.
- Operation and Maintenance Costs (O&M): are those that occur throughout the period under study, and in the case of lines and cables it is usual to consider them proportional to the size of the network and are a function of the types of feeders used. In the present work a constant (annual) cost of O&M of 3.8% of the initial investment was taken during all the years of the economic evaluation.
- Quality costs (CAL): Basically it refers to the costs attributable to interruptions in the supply, such as, for example, the costs of the energy that is left to be supplied or the possible compensations to the customers. They are difficult to evaluate and are the costs that can be associated with the poor quality of supply.

From a mathematical point of view, the different planning models try to minimize a Cost function (C), considering all or some of the terms mentioned above, subject to compliance with the supply constraints of the demand and the physical constraints of the network. For the formulation of the cost function (1), we assume that the quality goals for the networks under study are met and that the costs of O&M are proportional to the initial investment costs, keeping constant year after year throughout the planning horizon.

$$Min(Cost) = Min(C_{\text{Invest. Transf.}} + C_{\text{Invest. feeders}} + C_{\text{Loss}}) \quad (1)$$

Where C_x is the *Total Cost* of item x for all demand scenarios for the whole period under analysis (i.e. x= Investment in Transformers; x=Investments in Feeders; x= Losses).

Note: The total O&M costs for the entire evaluation period are added in these Total Investment Costs.

Subject to:

- Supply all the demand.
- Comply with the voltage regulation.
- Existence of a discrete set of feeders.
- Existence of a discrete set of transformers.
- Ensure the radial operation of the network.
- Respect the possible areas of the network.

In the previous economic equation (1) we can clearly distinguish two Costs from different natures:

- Costs due to investment, which are part of the fixed costs;
- Costs due to the technical losses of the network necessary to supply the demand, which have a variable cost nature (variable operating costs).

We can see that this minimum LCC (Life Cycle Cost) methodology considers the trade-off between the capital investment and the cost of the system losses for the optimal circuit design (the discount rate considered for this example was 10 %)

It should be noted that in this work we will see the opportunities in cost reduction in the case of incorporating Distributed Generation (DG) or Demand Response (DR), measuring its effect only on the feeders of the 31,5 kV (MV) level.

B. Power Flow Calculation

The calculation of the technical losses and the values of all the magnitudes of the system are simulated with a software that calculates a load flow using the Newton-Raphson method implemented according to [2] [4], the results were contrasted with the results obtained with the PSS®SINCAL [5]. Using this tool, a genetic algorithm was designed and implemented to evaluate the cost function for different combinations of feeders, verifying that it is capable of supplying (not only) the annual peak of demand. The cost function is evaluated for each combination of feeders taking into account the losses produced on them, and in case they do not meet some of the quality constraints imposed by the regulator entity, or violate feeders ampacity, this possible violations were included as barrier functions that penalizes the cost function to try to be minimized at the genetic algorithm. The program evaluates the physical magnitudes in each node of the network for this Base Case (at this time with the base case demand for all load scenarios for the entire evaluation period of 20 years).

Once the optimal base case network has been found (feeders for each section of the network that minimizes the investment plan for the base case) for the hole network planning horizon, the power flows are simulated again, including at this time different levels of DG and DR technologies penetration, using the same method for the calculation of the magnitudes in each one of the nodes and feeders to evaluate the potential of decrease/increase the costs of losses, and investment (changes in the type of feeder selected by the algorithm may occur) that could generate these technologies. Load flows were simulated for new scenarios of the year (8760 power flows) considering changes at the demand load curve due to the insertion of DG and DR, and for different levels of penetration of this technologies.

C. Methodology applied to a test network

The methodology used in the present work is:

1) We take a MV network with a given topology and a possible set of feeders to use, with their respective costs associated with the materials (including their installation) and O&M.
2) A base load scenario with given load curves is determined without applying any DG or DR incorporation plans.
3) We search and select (with the cost function), which is the network that minimizes the total cost equation to supply the demand at the load nodes, complying with the design constraints. For the exploration of the best configuration of feeders that presents the lowest total cost, a genetic algorithm is applied that looks for the best solution choosing the feeders taken from a set of possible standardized types (see Table I), and evaluates them in the cost function with their power losses, physical tolerances and each costs.
4) With the network solution found (base case) for the entire planning horizon, with demand states for each hour of the year, we compare this base case scenario with the scenarios where different DG and/or DR technologies incorporated at the Demand nodes, studying the results for different levels of penetration of DG or DR with respect to the original demand base case.
5) Finally, we studied the possible benefits/overrun-cost considering DG or DR in the calculation of the feeder of the new network, in comparison with the results obtained for the base case.

Operating procedure for the selection of the feeders is the same in all cases. For GA we use: 4 genes; 7 lines; 20 generations; 60 individual; 0.2 rate of mutation; 0.8 rate of cross.

III. Network Data

A. Schematic of the network

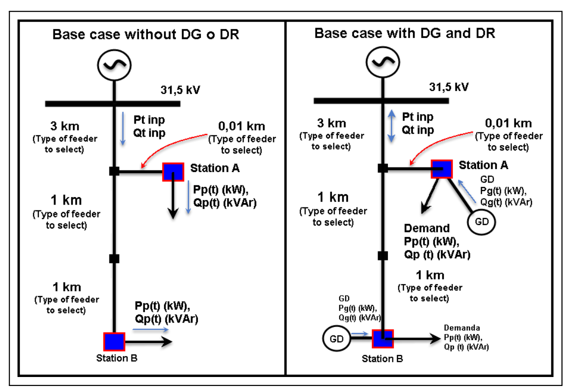

Fig. 1. Test Network without (left), and with (right) DG and DR.

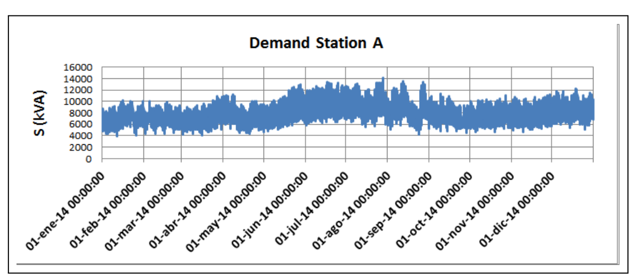

Fig. 2. Base case demand profile at Station A.

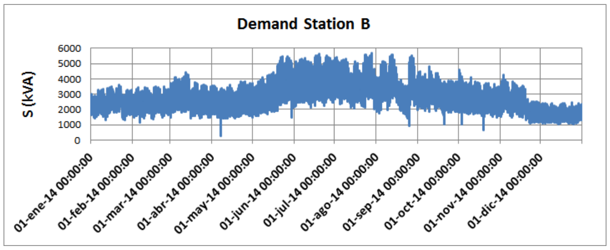

Fig. 3. Base case demand profile at Station B.

The demand loads aggregated at both Station is composed essentially with Residential customers.

B. Feeders

TABLE I
SET OF TYPE OF FEEDERS CONSIDERED TO BE ELECTED.

# Feeder	Type of Feeder	R (Ω/km)	X (Ω/km)	Ampacity (A)	Installation Cost (USD/km)
1	95/15ACSR (Overhead Line)	0.332	0.369	315	63.840
2	125/30ACSR (Overhead Line)	0.259	0.357	383	85.000
3	240/40ACSR (Overhead Line)	0.128	0.339	568	93.000
4	240ALXLPE (Underground)	0.161	0.113	415	250.000
5	500ALXLPE (Underground)	0.084	0.102	590	300.000

C. Photovoltaics (PV)

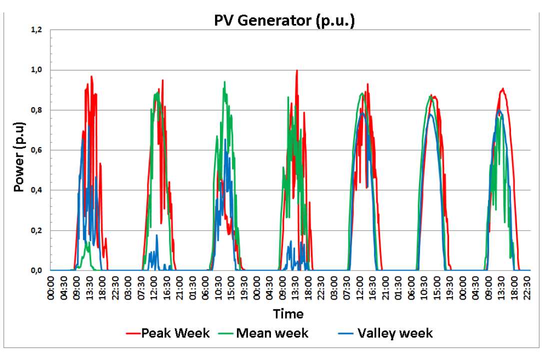

Fig. 4. Yearly PV generation curve (real historic values).

D. Wind (EOL)

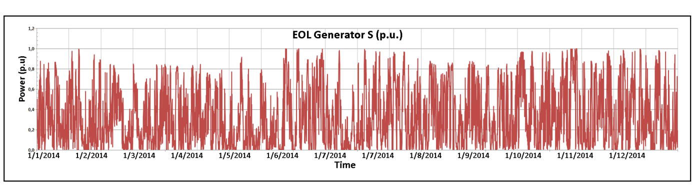

Fig. 5. Yearly Wind generation curve (real historic values).

E. Combined Heat and Power (CHP)

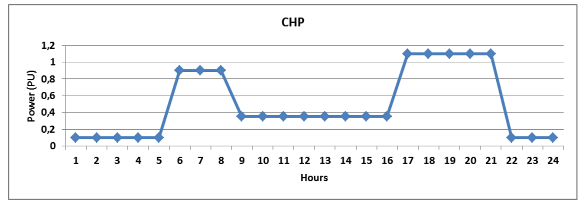

Fig. 6. Daily generation curve (p.u.).

F. Demand Response (DR)

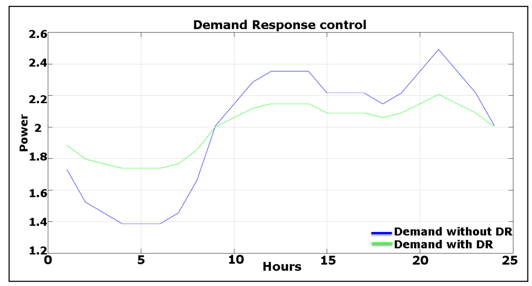

Fig. 7. Daily DR curves modified [6] (modified/non-modified).

IV. BASE CASE RESULTS (WITHOUT DG OR DR)

TABLE II
FEEDERS SELECTED FOR THE BASE CASE.

Feeder	# Feeder	Type of feeder selected
Line 1	3	240/40ACSR
Line 2	3	240/40ACSR
Line 3	3	240/40ACSR
Line 4	3	240/40ACSR

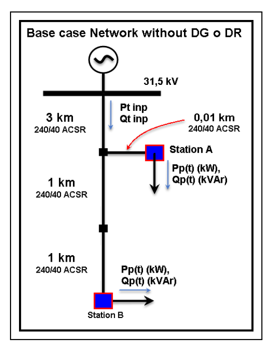

Fig. 8. Network result for the base case.

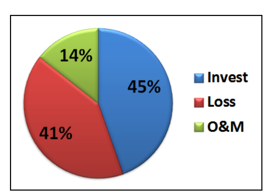

Fig. 9. Cost for the base case. Solution Type of feeders selected # 3 3 3 3.

V. DG and DR penetration results

A. Different percentage of penetration

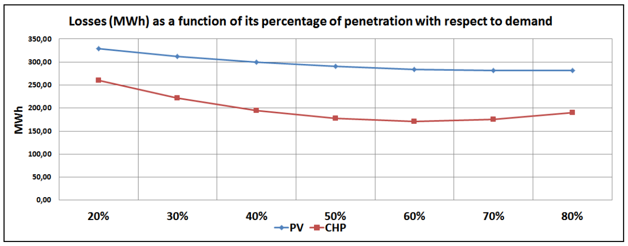

Fig. 10. Losses for different percentage of penetration.

Figure 10 shows the impact of the growing penetration of PV and CHP type in the total losses of the network of the base case. It is possible to see the decrease in technical losses with the increased penetration of these two types of DG. And we can also observe that an optimum point of penetration percentage close to 60% of peak demand is reached, with this type of DG units installed. Given that in urban areas (residential customers demand) the demand peaks usually occur at times where this type of generation has its contribution peaks, and as we reach higher levels of penetration of the GD happens to begin to give scenarios where the generation exceeds the minimum charges begin to cause reverse power flows from the stations to the sources. If we look at the effects for the PV, we see that its impact generates fewer benefits than in the case of the CHP, this is because in these types of urban demands, the load peaks are outside of daytime, where this type of GD has its generation peak, and during night-time peaks this type of GD doesn't contribute at all.

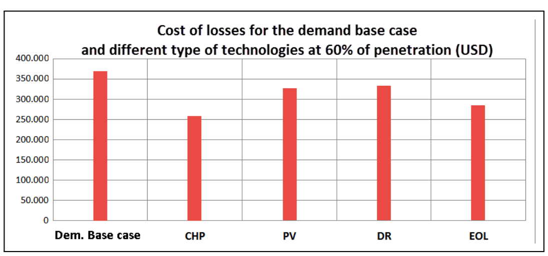

Fig. 11. Cost of losses for different technologies at 60 % level of penetration.

Figure 11 shows the impact on the network losses for 60% level of penetration of the different technologies and the base case demand (with no DG or DR intervention). **Note:** In the case of CHP, DR and EOL the feeders selected by the algorithm for this level of penetration is # 3 3 2 2.

VI. Conclusions

We have developed a tool created to carry out an economic evaluation and design a distribution network from the technical-economic point of view (the network that complies the Minimum Total Cost), considering a real annual demand curves with a horizon planning of 20 years. The optimal design of the networks from the technical-economic point of view was determined by minimizing the total costs of: equipment (considering its installation), Operation and Maintenance, and technical losses of the distribution network, ensuring compliance with all technical requirements.

A heuristic search method was developed to find the total least cost solution (for the entire horizon planning) among all the possible solutions (set of feeders available). The implementation of the genetic algorithm allows the use of the tool in the resolution of the problem for cases of more extensive and complex networks, where the number of possible combinations and necessary calculation capacity would make it practically impossible to exhaustively search for the best technical-economic solution.

After the design of the network capable of supplying the demand base case scenario, different options of Distributed Generation and Demand Response intervention at the demand nodes of the the stations is applied. The existence of an optimal limit of DG and DR penetration in the network selected was corroborated in terms of their contribution to generate benefits by reducing technical losses and their associated costs in the Distribution network [3].

We compared different types of DG and DR policies with different levels of penetration in this particular network and their relation with respect to the reduction of technical losses (variable costs). We verify that for this network with demands (mostly from residential urban circuits), CHP generation technology is the one that most contribute to flatten demands peaks (that occur generally at night, when customers are at home).

When we study the level of penetration of DG, we can see that the greatest benefit in the network for the case of the CHP occurs when we reach the 60% level of penetration in the network. When we evaluate the case of PV technology, we see that if we increase the level percentage of penetration with respect to demand, there is a deceleration in benefits due to the reduction of technical losses.

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