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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Analysis of demand response solutions for congestion management in distribution networks: a real case study

TESI MAGISTRALE IN ENERGY AND MANAGEMENT ENGINEERING – INGEGNERIA ENERGETICA E GESTIONALE

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ACADEMIC YEAR: 2021-2022

1. Introduction

Distributed energy resources (DER), such as distributed generation, energy storage systems, and new types of consumer devices, like heat pumps and electric vehicles are the new elements of the distribution grids. This is the result of the intensifying efforts to reduce CO2 emissions and improve energy efficiency [1]. The operation strategies and the management of distribution networks are changing because of the inclusion of these new components. This led to a shift from the "fit and forget" to the "fit and manage" paradigm, meaning that an active network management is needed [2]. Out-of-range voltages and electric power congestions are two of the main issues in which the distribution grid can currently incur in. The former is caused by the distributed generation which impacts grid voltage profiles by raising them. The latter happens when a grid component's carrying capacity is exceeded by the amount of power flowing through it. The arise of these issues could be easily anticipated in advance in the formerly passive networks, but nowadays it occurs with a very brief warning, necessitating rapid action. The conventional solution was the grid reinforcement, through a physical grid extension (GE) of the infrastructure. The GE solution requires a long reference time horizon, for the planning phase and the construction works, and very high CAPEX. For these reasons, it might not be anymore the optimal solution to tackle grid issues. In this context, one of the alternative solutions for the distribution system operator (DSO) is to use flexibility provided by the users connected to the grid, called flexible resources, to make the distribution networks more responsive and resilient toward demand profiles with high uncertainties and rapid variations. A potential approach for the provision of flexibility is the demand response (DR). It consists in partially curtailing the load during peak hours to free up system capacity in the reference time period and prevent the formation of congestions. Due to financial savings and environmental advantages of deferring plans for system development, DR has emerged as a viable alternative to GE [3]. It is important to highlight that DR initiatives on the transmission grid have already been implemented across Europe, however the application on the distribution grid is still limited to a few pilot projects [4]. Focusing on Italy, the latest resolutions by the Regulatory Authority for Energy (ARERA) have encouraged the arrangement of pilot projects to test different ways of procuring flexibility on distribution grids [5]. The objective of this thesis work is to verify the technical feasibility of the DR to prevent grid congestions and to compare the costs for implementing such solutions as an alternative to GE.

2. Demand response and Grid extension cost structure

Depending on the typology of the active resource involved, the DR could lead to a potential discomfort (in case of domestic users) or a loss due to the missed production (in case of industrial users). The inconvenience needs to be remunerated by the DSO. The remuneration to the flexible resources is the main cost item since European distribution grids operators are already installing the enabling technologies, such as smart meters [6]. The quantification of the economic reimbursement is thus very aleatory, depending on the specific conditions of the resource providing the flexibility. The tariff can be composed by two parts: a fixed annual part related to the capacity made available [€/MW] and a variable part proportional to the actual activation of the flexibility [€/MWh].
Regarding the GE, the cost is based on the forecasts made for each year until the end of the planning horizon. If a branch is expected to exceed the maximum capacity, the solution consists in reinforcing the feeder with another cable in parallel. Thus, the estimation of the GE cost consists in the quantification of the cost of the new cables and for the construction work. Even though these costs are very site specific, depending on the grid topology and the type of terrain, the information contained in "Technical rules for connections" document, published by each Italian DSO, can lead to an identification of a lower limit [7] . Thus, for each grid scenario, the GE cost is taken as the benchmark and then a sensitivity analysis is conducted regarding the DR costs.

3. Methodology

Four main phases are necessary to reach the objective of the thesis. The first phase regards definition and formalization of the two proposed solutions. In the second phase both solutions are tested to validate their robustness and accuracy on made-up grids. In the third phase they are applied to the real grid of Trieste, using as inputs real data. The fourth phase is the techno-economic analysis of the results obtained.

The DR and GE are simulated using an algorithm for each one of the solutions. Before describing the algorithm is it necessary to define the process which leads to the generation of the inputs, shown in Figure 3.1.

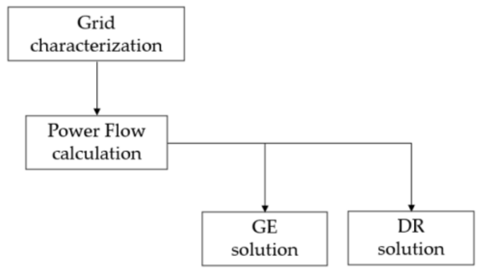

Figure 3.1: description of the input generation

The grid characterization is divided in two phases: grid parameters definition (branches, nodes and electric parameters) and loads and generators energy profiles upload. Then with a Power Flow procedure all the electric results (such as power, currents and voltages) are calculated for each time step. The Power Flow outputs are the input for the GE and DR solution.

3.1. Demand response solution

The first phase is the characterization of all the active resources present on the grid, according to different parameters such as the distance from the substation and the path in which the load is located. In fact, distribution grids are built radially, as shown in Figure 3.2, meaning that from the substation (represented by Node 1) different path can ramify.

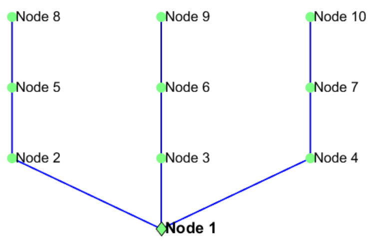

Figure 3.2: distribution grid topology

The way in which the active resources can offer their flexibility service is through a local market, in which the DSO is the central counterpart. Each resource can bid three different offers, characterized by a price [€/MWh] and the quota of power [MW] they are willing to reduce for each hour. For sake of simplicity, only the active power is considered for the reduction. Then, the actual DR algorithm can start. For each time step and branch of the grid, a check is made on the presence of a congestion. When this is the case, only offers made by the flexible resources which are technically able of alleviating the congestion are considered. This happens when two conditions are verified: the load is located downstream the congested branch and it is on the same path. The DSO sorts all the bids in order of increasing price and when one is accepted the relative active power is reduced according to the offered quantity. Since the reduction of power is small compared to the overall quantity, the voltage on the node is assumed to be constant. This operation is repeated iteratively until either the congestion is solved or the flexible resources available finish. The output of the algorithm are all the updated electric variables and the hourly cost to solve the congestions.

3.2. Grid extension solution

The first part of the algorithm is shared with the DR one, consisting in the identification of the congested branches. The difference between the current that would need to flow to satisfy the electric demand and the cable maximum carrying capacity is calculated for each branch and for every time step in which a congestion has been detected. The value corresponding to the 90th percentile for each branch along the time horizon considered is the one taken as the reference value. These values represent the capacity of the cable that needs to be added in parallel to the existing one in order to prevent the formation of the congestion. Based on that, for each branch the most suitable cable to be added is selected and the relative cost of the operation is calculated. Given the fact that the choice for the cables on the market is limited, in many cases the new branch will be over-dimensioned with respect to the real necessities. The yearly cost is found by dividing the total cost of the cable and the construction work by the useful life, which is assumed to be 30 years [7].

3.3. Execution of the algorithms

After defining the algorithms for the two solutions, the methodology is validated by the application on a test made-up grid. Different cases are analyzed by changing with different combinations the following parameters: the branches' maximum carrying capacity and length, the nominal power of the loads, the length of the branches and the price of the DR bids. This operation is done also to detect trends in the final prices of the two solutions with respect to the different input data. As expected, the initial data strongly influence the final results, confirming the high case specificity of the analysis. The DR solution is more convenient with low number of congestions in the considered time horizon and with a limited amplitude. These conditions advantage the DR solutions because only the exact needed flexibility is activated. On the other hand, the GE could lead to grids which are over-dimensioned, and the investment needs to be made regardless of the number of hours in which the grid can incur in a congestion. The length of the lines is also a crucial factor since it is one of the main drivers of the cost of the GE. And lastly, the prices of the bids are the main driver for the price of the DR.

4. Application to the distribution grid of Trieste

After the methodology has been validated, it is possible to apply the two solutions on the distribution grid of the city of Trieste (Italy). The simulations have a timestep of 1 hour and a time horizon of 1 year. The grid is built with real data for the electric parameters and topology, and an average between historic series of the years 2018 and 2019 is used to model the energy profiles of the users. In the grid there are 11 primary substations, 86 users (either pure loads or prosumers), 88 nodes and 91 branches. Each user is served by only 1 substation since the grid is perfectly radial. There are interconnection points between different lines, but in normal conditions they are not activated. The assumption is that each load present in the grid participates to the DR scheme, offering a maximum reduction of the active power of 35% with respect to its demand in every time step.

4.1. Grid in normal conditions

The first part of the analysis focuses on the grid in normal conditions, without any faults. Figure 4.1.1 shows the average loading of each line calculated as the ratio between current flowing in the branch and the maximum carrying capacity for each hour.

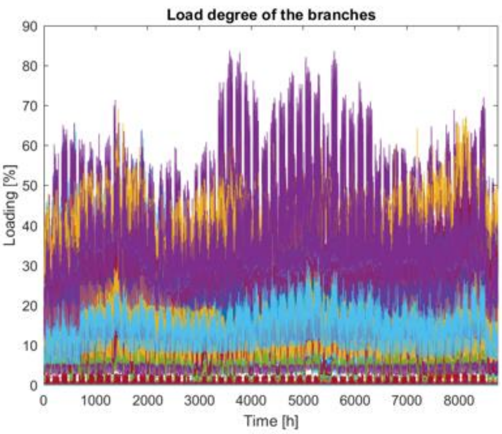

Figure 4.1.1: loading in normal conditions

It is immediate to notice that in normal conditions the maximum loading reached is only 80%, since the grid is already over-dimensioned to avoid the formation of congestions, as it is common to do in distribution grids. In Table 4.1.1 it is possible to see how the results change if the nominal active power demand increases.

Power demand	Maximum loading	N° congeste d branches	Annual cost of GE solution [€]
+5%	86.8%	0	0
+10 %	92.2%	0	0
+15%	96.5%	0	0
+ 20%	101%	1	949.56
+25%	105%	2	2269.77

Table 4.1.1: sensitivity analysis on the power demand

Regarding the DR, it is not possible to identify a single cost for each scenario, since the result is influenced by the price of each bid which is randomly generated. For the case +20% the average price for the DR solution never overcomes 870 €/year, if only bids lower than 350 €/MWh are accepted. When the demand increase reaches the value of +25% the GE becomes more convenient than the DR, regardless of the bids' prices. According to the TERNA scenarios, a demand increase of +20% is not expected for at least the next 15 years [8]. Thus, in normal operating conditions neither of the two solutions should be requested in the short time. However, the power demand forecast needs to be constantly updated and if an increase of the active power of +25% is expected in the future, the GE would be the most convenient solution. The DR can be a transitional solution to cover the technical time for the eventual construction work, or to solve the congestions caused by unexpected peaks.

4.2. Grid in fault conditions

The second parts focuses on the grid when there is a fault in a branch connecting two nodes: to reach the users that are downstream the failure a counter-feeding is necessary, and it is done through the inter-connection point of different lines. This situation can be critical for the grid stability since the lines which are used for the counter-feeding are heavily loaded and could incur in a congestion much more likely than in a normal condition scenario. A simulation of a fault in each branch of the Trieste grid is conducted. It is possible to identify 4 main different cases in which the fault leads to the formation of one or more congestions in the respective line. For each case, the fault is simulated starting from the most upstream branch (the worst case in term of congestions) and then is moved downstream the line until the number of possible yearly congestion is reduced to zero. In Case 1,2 and 3 two different grid re-configurations are possible for the counter-feeding, whereas in Case 4 there is only one possible. The electric results and the cost of the GE solution for each case can be seen in Table 4.2.1.

Case number	Maximum loading	N° congested branches	Annual cost of GE solution [€]
1A	126%	1	349
1B	123%	6	6510
2A	123%	7	10597
2B	118%	7	14348

3A	105%	9	4244
3B	106%	1	349
4	129.5%	14	23048

Table 4.2.1: summary of electric results and GE cost

5.1. Economic comparison of the solutions

In order to adopt a more conservative approach, the comparison is done considering the worst situation for each of the cases, with the fault simulated as close as possible to the primary sub-station. Since no data were available about the frequency of a fault for each branch, a probabilistic approach needs to be adopted. Thus, 5 different indicators are defined to support the analysis. Since the GE solution does not depend on the assumption made about the presence of the fault, but only on the maximum values of current, which is solely dependent on the power demand, the different indicators concern only the estimate of the cost of the DR solution. For each indicator a sensitivity analysis is done on the price of the bids, using as maximum value 400 €/MWh, the same as the strike price for the demand response in pilot projects in Italy on the transmission grid. The indicators are the following:

- I: the cost is calculated for each hour by applying the DR algorithm to each case, as if the fault was present all year long. This indicator is useful to understand the cost of solving the single congestions.
- II: an average yearly cost is calculated assuming only one fault per year with a duration of 1 hour, starting from the hourly results of Indicator 1, using (5.1). Since different cases have a different number of congestions, this indicator is useful to make comparisons.

$$cost_{average,DR} = \frac{\sum_{i=1}^{number\ of\ congestions} cost_i}{number\ of\ congestions} \quad (5.1)$$

- III: the cost is calculated assuming that every time a congestion starts it lasts until the demand spontaneously decreases, without the fault being resolved. Thus, each congestion has a different duration which depends on the energy profiles of the loads. The indicator is the ratio between the number of congestion events that are less costly than the GE, and the total number of congestion events.
- IV: starting from the results of Indicator 1, the final cost is calculated assuming that the fault coincides only with the highest demand peaks, leading to the congestions with the highest amplitude. The indicator is the sum of the hourly cost of the given congestions. It is used to understand the cost in the worst conditions.
- V: the cost is calculated doing a sensitivity analysis on the number of hours in which the branch is congested, starting from the results of Indicator II, as shown in (5.2).

$$cost_{n\ congestions,} = cost_{1\ congestion} \times n \quad (5.2)$$

In the indicators I to IV the comparison is done between the DR and GE cost considering the same re-configuration for each case. With indicator V the difference is that the comparison is done considering all the possible re-configurations, when possible, to find the cheapest alternative.
Considering all the indicators altogether, it emerges that in two out of four cases the DR can be much more convenient than the GE. The most relevant results are shown in Table 5.1.1. For Indicator 1 it is shown the maximum hourly price, for Indicator IV the results are related to the 5 worst congestions and Indicator V shows the average price for 10 yearly congestions. To be more conservative, all the results shown are calculated with the highest price range for the bids.

	I [€/y]	II [€/y]	III	IV [€/y]	V [€/y]
1A	1252	355	32%	8154	4054
1B	11258	361	100%	5896	4783
2A	1232	293	97%	4434	3845
2B	1115	625	100%	2145	4738
3A	286	291	100%	291	502
3B	351	301	57%	1765	1697
4	7232	988	90%	32001	9984

Table 5.1.1: summary of the results

In Case 2 the DR solution is estimated to be less than the reference GE for Case 2 (10597 €/year) for all the indicators, meaning that it is very likely to be more convenient. In Case 4 the DR solutions is cheaper than the GE (23048 €) in 4 out 5 Indicators.

Even if in Indicator 4, the most pessimistic, the DR cost is higher than the GE it is still probably more convenient to pursue the DR solution. In fact, in this Case the initial investment is very relevant, and it is unlikely that the worst conditions happen in more years along the time horizon. Thus, a loss in one year is compensated by the economic savings of all the others. In Case 1 and Case 4 it may be more reliable to pursue the traditional GE solution, which costs 349 €/year for both cases. It is quite a low value and in many cases is overcome by the cost of the DR. However, a DSO with a high-risk profile could still choose the DR solution and save money, since all the analysis carried out are conservative and consider the worst scenarios. In fact, it is possible for all the Cases that a congestion never appears along the year because any fault is present or that a fault is present in a moment of time with low demand. In this case, the avoided expense for the DSO coincide with the full yearly cost of the GE solution, since the cost for the DR solution would be 0 €.

5.2. Flexible resources utilization

Based on their placement on the grid, different flexible resources have a different likelihood that their bids are accepted by the DSO over the course of a year. This is a direct consequence of the structure of the DR algorithm. The findings demonstrate that, in each case, one or more resources have a greater likelihood than the others of having their bids accepted. In Case 2 they are the resources at the end of the congested line, whereas in Case 4 they are the resources located in the middle of the line. This is a direct consequence of the topology of the different line which influences how the counter-feeding is done. The DSO must consider these patterns when deciding whether to permit a flexible resource to participate in the DR scheme. In fact, if a capacity-based part of the tariff is set up, the loads that were not chosen for flexibility at the end of the year still need to be remunerated. The simulations showed that the capacity-based tariff have a structural limit of 441 €/MW in Case 2 and 960.33 €/MW in Case 4, due to the fact that the maximum budget is constrained by the yearly price of the alternative GE solution.

6. Conclusions

The aim of this work was to develop a model to compare innovative demand response and conventional grid extension as potential solutions to manage the congestions on the distribution grid Three key conceptual differences between the two solutions have emerged. The first one is the cost structure: GE has low OPEX and high CAPEX, DR has high OPEX and low CAPEX. The second one is the applicability period. When a grid congestion is already present or is simply being predicted to occur soon, the DR method is designed to work very nearly to the real time. The GE solution, on the other hand, is based on projections of the evolution of the supply and demand profiles for electricity. In order to be carried out, significant construction projects must be planned and forecasted years before the potential formation of the congestion. The third difference is that the DR solution is naturally constrained by the active participation of the loads and by the amount of active power that they are ready to sacrifice. In contrast, the GE method is theoretically always effective because the DSO can arbitrarily expand the grid's capacity. The two solutions have been applied using real data for the distribution grid of Trieste, simulating one year with an hourly resolution. Different simulations have been conducted, both in normal operating conditions and with the presence of a fault. The results have shown that in normal operating conditions neither solution should be applied in the short term. This is due to the fact that the grid is already over-dimensioned, and the presence of congestions is not forecasted. On the other hand, regarding the fault scenarios, relying on the flexibility options that demand significantly fewer CAPEX investments is statistically more economically advantageous, since the probability that the presence of the fault will coincide with the high-power demand is not high, even though difficult to precisely quantify. Adopting a DR scheme in some cases could lead the DSO to save an economic expense of hundreds of thousands of euros. The analysis have also shown that this type of analysis on a distribution grid is very case specific, for both solutions. Thus, the same approach replicated to a different case study could lead to different conclusion regarding the convenience of one solution with respect to the other.

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