Valorization of Demand Response for Voltage Control in MV Distribution Grids with distributed generation

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***Abstract*—This paper presents a methodology for the contribution of demand response in reducing the cost of voltage control in radial distribution grid with distributed generators (DG). The bidirectional power flow in the active distribution network can introduce voltage issues that impede the integration of DG. Due to this fact, the distribution system operator (DSO) has to enhance the lines in the grid or curtail the power output of DG in case of constraint. The possibility of using the flexibility of demand to cope with the voltage constraint is investigated in this paper. The results are promising that by using the demand response, it is able to reduce the active curtailment of DG and postpone the investment of grid reinforcement.**

***Index Terms*— Active Distribution Networks; distributes generators; demand response; valorization**

I. Introduction

The growth of distributed generations (DG), rendering actual distribution networks to become more active, will bring a massive number of impacts on network operation [1]. One of them is the voltage issue since the distribution network has become more dynamic with bidirectional power flow. This problem has been addressed by most publications (ex. [2]) using the regulation of reactive power, especially from the DG unit. However, the reactive power injection (or absorption) by DG is limited by the capacity of its converter, and this limitation is more important as the voltage level is lower [3]. The active power curtailment of DG can be a solution when other voltage control means are insufficient ([4]), although it will reduce the revenue of DG owner. In [5], reactive power services and active power curtailment methods have been implemented for voltage mitigation.

Using the flexible load as a storage solution has been investigated for the possibility of voltage control in distribution networks [6]. In fact, in the distribution network the active power can influence on the voltage as well as or even more significantly than the reactive power due to the high R/X ratio. In [7] the authors propose an emergency demand response program based on voltage sensitivity in order to maintain the voltage profile within the admissible limits, but the coordination with DG services is not concerned. The sensitivity coupling of voltage and demand can be used when implementing demand response for voltage support ([8]).

If flexible loads can help for the voltage control, there still remains a critical issue: which remuneration for the consumers or the aggregators? Presently, the flexible demand is mainly valorized in the balancing markets or in the capacity markets, and even in frequency control market (an experiment is conducted with the French TSO). In that case the remuneration does not depend on the flexible load location. But controllable loads can help in solving congestions or voltage local constraints where their location will be critical. If we consider a radial MV feeder with voltage drops, 1MW of flexibility will have a greater value at its remote end than at its head.

The present paper is dedicated to the integration of DG in MV distribution grids by voltage support and an evaluation of how much the demand response can help to reduce or to postpone investment costs or DG curtailment cost that would be required to comply operation constraints. This will be a first step towards the valorization of the demand response for distribution grids.

The present paper is organized as following: the section II introduces the voltage issues that may occur in an active distribution network (ADN). To cope with these constraints, the demand response could be used in stead of grid reinforcement. The section III presents a voltage control approach using the DG services and demand response. The objective is to minimize the voltage control costs by using different resources. Different scenarii have been tested to compare the performance of voltage control. The section IV presents the results of voltage control in different scernarii. Moreover, the performance of demand response is discussed in keeping with the demand growth. Finally, a conclusion is given in section V.

II. VOLTAGE ISSUE ON AN ACTIVE DISTUIBUTION GRID

Considering one node is at a remote feeder location with DG and load as shown in Fig. 1:

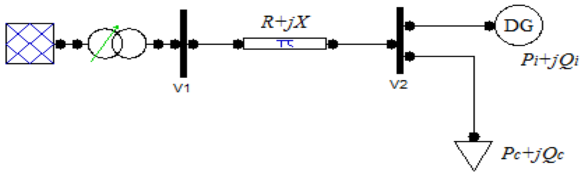

Figure 1. One single feeder connected with DG

where P_i+jQ_i denotes the power injection of DG at the bus of connection, P_c+jQ_c presents all load consumption in the downstream buses, $R+jX$ the resistance and reactance of the feeder.

The voltage drop at this node is approximately equal to:

$$\Delta V = \frac{(P_i - P_c)\cdot R + (Q_i - Q_c)\cdot X}{(V_1 + V_2)/2} \tag{1}$$

The voltage issues due to DG possibly occur: 1) when heavy DG and weak load; 2) when weak DG and heavy load. They respectively correspond to voltage rise and low voltage problem, according to the equation 1.

The conventional voltage control means, as known as tap changer or OLTC, is not designed for the voltage issue due to inversed power flow. To remove the network constraints, the DSO is required to reinforce the lines of grid. The measures for grid reinforcement can be installation of an additional cable, or replacement of overhead lines with higher cross-section cables, or reactive power compensation ([9]). All of them have considerable costs for the DSO. For example, the construction of a new HV/MV transformer can reach 150k€ (see [10]).

In an ADN, with the implementation of smart grid infrastructures, the DSO will be able to monitor the grid and even modulate the flexible load and generation profiles by some active network measures, including reactive power control by DG inverters, limit active power injection by DG and demand response, potentially.

From the equation 1, the modulation of load and generation can be used to limit the voltage if voltage violations occur. It must be noticed that, the active power of DG and the demand response can influence on the voltage as well as or even more significantly than the reactive power due to the fact that the ratio R/X≈1. By implementing the voltage control strategies with active network measures in an ADN, the network constraints can be mitigated in keeping with the increase of load and DG integration. The issue could be interesting to the DSO whether these measures can reduce the maintenance costs of DSO, especially for the investment of grid reinforcement.

III. VOLTAGE CONTROL WITH DEMAND RESPONSE

A. *Costs of Demand Response and Voltage Support*

By comparing with grid reinforcement, the active network measures have much fewer costs as reinforcement costs are often dominated by the construction costs. The costs of active network measures could be not only the real payment by the DSO but also the losses of the "social welfare", such as the revenue losses of DG owners or the system losses in the grid.

In practice most aggregators of DG must provide the reactive services as a contracted condition for the connection of DG within the grid. The DSO will not pay for the reactive power provided by DG, so it is difficult to estimate the value of reactive services. In fact, the reactive power will influence the power flow in the lines and increase system losses in the grid. Thus the cost of reactive power is estimated by multiplying the loss sensitivity coefficient with the market spot price. The source of market spot price during one year used in this paper is obtained from EpexSpot (European exchange for power trading). The loss sensitivity coefficient can be calculated from the grid data.

The costs of demand response can be the influence on the comfort of load consumers. There are many methods to evaluate the costs of demand response. In this paper we define the costs as the payment of demand response in the national energy market, and the tariff adopted by French utility which is dependent on low/peak hours and different seasons, as shown in table I.

TABLE I. COSTS OF DEMAND RESPONSE

Tariff (€/MWh)	Winter Q1	Spring Q2	Summer Q3	Autumn Q4
Peak hours	64.08	42.18	42.25	60.68
Low hours	45.67	28.49	28.06	43.61

The peak hours are from 8h to 20h of the working days. The low hours are from 20h to the 8h of next day of the working days and the whole day of weekend. The costs are higher in winter and in spring due to the thermal demand.

The active curtailment of DG is also unpaid by the DSO but it reduces the revenue for the DG owner. Moreover, the power of DG is clean and without CO2 emission. As the marginal power production cost of renewable resource is zero, the active curtailment cost per unit for the DG owner is estimated as the market spot price.

The costs of tap changer are calculated from the maintenance cost. It is assumed that the maintenance cost of each year is 0.5% of investment cost. The daily operation of tap changer is about 1~2 times. If the tap changer is operated more frequently, the DSO must take into consideration the wear of device.

B. *Optimization of Voltage Control with DG Services & DR*

The voltage control in an ADN by the DSO can be coordinated through a centralized optimization. Here we formulate a mixed-integer linear programming (MILP) problem to compute the use of each means for voltage control. The objective function is the total costs of concerned voltage control means:

$$\min\langle \gamma \cdot C_1 \Delta tap + C_2 \Delta Q_{DG} + C_3 \Delta P_{DG} + C_4 \Delta P_{DR} \rangle \quad (2)$$

where the factors C_1, C_2, C_3 and C_4 are respectively costs using the tap changer, reactive and active power of DG, as well as demand response. γ is DSO preference of using tap changer from 0 to 1, which correspond to an extremely willing case and unwilling case, respectively.

The optimization is subject to the constraints of equality (3) and inequality (4-8):

$$\Delta V = S_T \Delta tap + S_Q \Delta Q_{DG} + S_P \Delta P_{DG} + S_{DR} \Delta P_{DR} \quad (3)$$

$$V_{\min} \le V_0 + \Delta V \le V_{\max} \quad (4)$$

$$tap_{\min} \le tap_0 + \Delta tap \le tap_{\max} \quad (5)$$

$$Q_{DG}^{\min} \le Q_{DG} + \Delta Q_{DG} \le Q_{DG}^{\max} \quad (6)$$

$$P_{DG}^{\min} \le P_{DG} + \Delta P_{DG} \le P_{DG}^{\max} \quad (7)$$

$$\Delta P_{DR}^{\min} \le \Delta P_{DR} \le \Delta P_{DR}^{\max} \quad (8)$$

The equation 3 represents a linear approximation of voltage-power coupling in the grid. The voltage sensitivity coefficients S_T, S_Q, S_P and S_{DR} are computed using the grid data and load/generation profiles. Other constraints 4-8 define the admissible limit of voltage and control variables.

The MILP problem is resolved for one spot of the demand and generation pattern, with the sampling density of 30 minutes. This hypothesis is related to the limit of smart meters in each bus. Thus, there are 365*48=17520 spots over one year and the total costs can be obtained from the sum of all spots.

C. Scenarii of Test

The proposed approach of voltage control has been tested in a modified IEEE 34-node distribution feeder presented in figure 2. More details of the grid data can be found in Appendix. The main modifications comprise removing two line voltage regulators and adjusting the characteristics of lines in accordance with the practice of French utilities. Two wind generators are connected within the grid to simulate the high penetration of renewable energy resources.

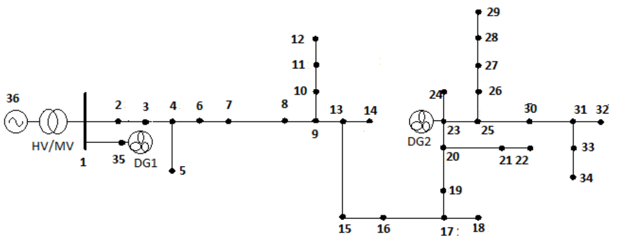

Figure 2. Single line diagram of test feeder

The maximum power output of DG1 and DG2 is respectively 4.4MW and 3.2MW. The load and generation patterns in the basic case are extracted from the historical data in the region of Provence in France, provided in the document of ERDF (the main French DSO). The load profile over one year is shown in fig.3. The load flow calculations are performed repeatedly for each checkpoint of 30 minutes using the MATPOWER toolbox [11].The voltage limits in this feeder is set to the range [0.95*pu*, 1.05*pu*].

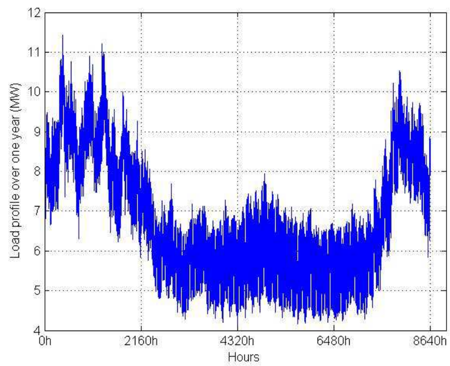

Figure 3. Load profile over one year

It is noticed that during the winter and early spring, the heavy heating demand triggers huge electricity consumption, which probably introduces more voltage violations.

The voltage control in the distribution grid is performed in a basic case and four scenarii: (1) tap changer, DG reactive services, and DG active curtailment; (2) tap changer, DG reactive services and DR, but without DG active curtailment; (3) tap changer, DG reactive services, DR and DG under minimization of active curtailment, and (4) grid reinforcement with all overhead lines changed for underground cables with a classical network operation (only tap changer is used and DG with a fixed unity power factor, and neither active network measure is not used). In each scenario, the variable non-concerned is set to 0 in order not to be used in voltage control.

IV. Main Results and Discussions

A. Voltage Profiles with Different Cases of Voltage Support

The voltage profiles over one year have been computed firstly with a basic case. For the sake of simplicity, the maximum, minimum and mean values of the voltage magnitude at each bus are shown in fig.4. In this case neither the active network measure nor grid reinforcement is used.

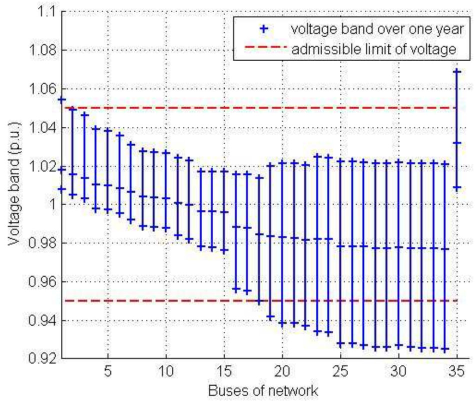

Figure 4. Voltage profile of the basic case

The tap changer is the unique means of voltage control in the basic case. It could be found that the voltage has dropped below the lower limit among the downstream buses. This is because the setpoint of tap changer is adjusted downward to handle the voltage rise at the bus of 35. Actually, the maximum voltage at the bus of 35 has still exceeded the upper limit due to the penetration of DG1. The voltage magnitude around the bus of 23 is raised as the DG connected nearly with the load consumption is able to improve the voltage profile. The voltage still can become under the lower limit, especially when the output of DG2 is weak. The tap changer switching number is 1897 times, which implicates a frequent operation that increases the wear of tap changer.

The voltage profiles with the four scenarii have been shown in fig. 5~8. As expected, all the measures have improved the voltage profiles. The detailed results of voltage control are shown in table II. The occurrences of voltage violations at the busses 34 and 35 are presented since these buses are representative for the low voltage and voltage rise issues.

In scenario 1, the active curtailment of DG is used when tap changer and reactive services are not able to remove the voltage violation. In the scenario 2, when the DG has to be curtailed, the demand response is solicited so the voltage constraints can be removed while the DG can still connect within the grid. So the costs of scenario 2 are reduced with comparison of scenario 1. However, given the flexible loads take part of the 30%, the DR cannot remove all voltage constraints as shown in the figure 6.

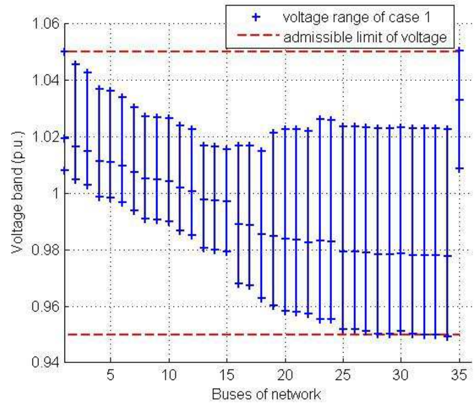

Figure 5. Voltage profile of the scenario 1

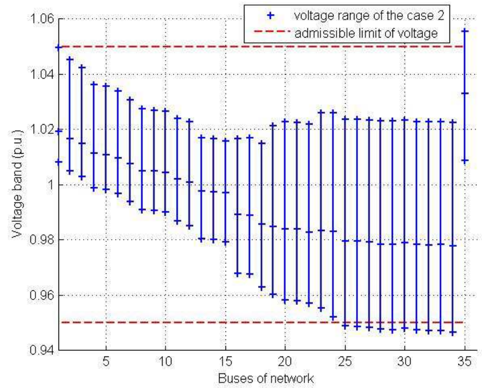

Figure 6. Voltage profile of the scenario 2

In scenario 3, the active power curtailment is under optimization if the demand response is not sufficient to remove the voltage violation. Due to the demand response, the part of active curtailment is less than the scenario 1 without DR. Thus, the cost of the scenario 3 is slightly raised in comparison with the scenario 2, but still less than the scenario 1.

TABLE II. PERFORMANCE OF VOLTAGE CONTROL WITH DIFFERENT SCENARII

Voltage control scenario	Number of voltage violation times/year			Tap changer switching number	Curtailment of DG (MWh/year)		DG active curtailment costs (k€/year)	DR costs (k€/year)	Total costs of voltage control (k€/year)
	All	Bus 34	Bus 35		DG1	DG2			
Basic case	1087	122	108	1897	0	0	0	0	N/A
Scenario1	0	0	0	989	17.8	0	1.086	0	11.8
Scenario 2	16	3	10	947	0	0	0	0.601	11.3
Scenario 3	0	0	0	1067	14.6	0	0.905	0.584	11.5
Scenario 4	5	0	5	652	0	0	0	0	132.6

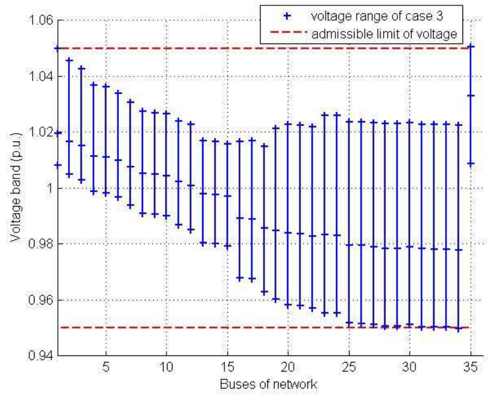

Figure 7. Voltage profile of the scenario 3

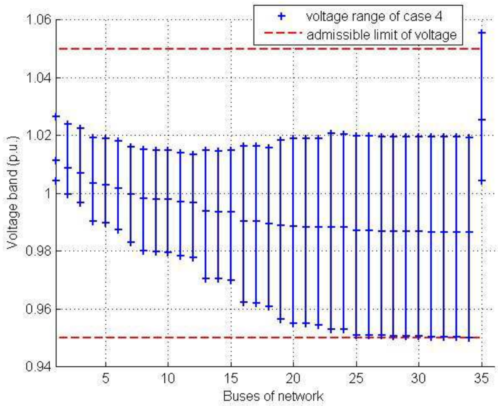

Figure 8. Voltage profile of the scenario 4

In the scenario 4 all overhead lines have been replaced to underground cables as the latter is with a larger across-section and less impedance per km. The total length that requires reinforcing is 39.765 km (overhead lines shown in Appendix). The cost of reinforcement per km with cables in the rural MV grid is estimated 50~150k€/km (see [12]). We assume the median value 100k€/km and the grid will work for 30 years until the next reinforcement. In this scenario the voltage drop on the lines is much weaker and the feeder has more voltage margin to host the DG penetration. It cannot totally remove the voltage constraints especially for the bus with DG1 since the DG services are not used. It has to be remarked that the costs of reinforcement are considerably higher than the other means, since it is dependent on the construction costs.

Compared with the basic case, all four scenarii allow great reduction of tap changer operation, since these voltage support means can alleviate the burden of tap changer. The benefit of reducing the wear of device must be taken into account.

Among these four scenarii, it can be concluded that the participation of DR is capable of voltage support but it is not sufficient to totally replace the active curtailment of DG. However, the combination of the DG services and DR can provide enough voltage support to host the maximum of power of DG. Thus, it is reasonable to adopt the DG services and demand response instead of grid reinforcement.

B. *Analysis of Demand Growth*

It seems that the DG services and demand response are capable of removing the voltage violations at the actual level of demand. However, the next challenge is if the demand keeps increasing, this conclusion is still stand by and how the costs of voltage control will increase. For the sake of simplicity, we assume that the demand growth is 1% per year uniformly. The evolution of the number of voltage violations per year is shown in fig.5 for the 4 scenarii.

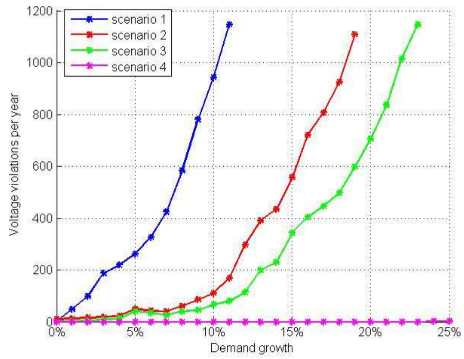

Figure 5. Voltage violations with demand growth

It can be seen that at the beginning the number of violations is very few, as same as the table II shown. Then the curve of scenario 1 increases quickly. This is because there is little voltage margin for the initial network situation. For example, when demand increases 10%, the number per year of each scenario is respectively 947, 106, 76 and 5. As the demand increasing, it is much more difficult to mitigate the voltage violation through DG services if the demand is heavy.

The scenarii 2 & 3 have shown better performance of limiting voltage violations, due to the demand flexibility. The demand response can be used in case the voltage margin is not sufficient when the DG services are used. So there are less voltage violations than the scenario 1. If we assume the voltage violations should not exceed 100 times per year and otherwise the grid reinforcement has to be implemented, the scenario 1 will reach this threshold in 3 years while the scenarii 2 and 3 are respectively in 10 years and in 12 years.

V. CONCLUSIONS

It can be concluded, that the demand response is able to contribute to the integration of DG in the distribution grid, as it is able to mitigate the negative impact by the penetration of DG. In participating on voltage control, the demand response, as a complement of voltage support, helps removing the voltage constraints when the DG services and other means are insufficient.

Although the voltage issues depend on the specific feeder, the paper proposes a methodology and the results are promising for the valorization of demand response in distribution grids. The table II shows that DR is cheaper than DG, even if the global cost of all scenarios is almost constant due to the large contribution of the OLTC. The costs of voltage control with DR and DG services are significantly less than the grid reinforcement. It must be noticed that the use of

DR is less efficient than DG, since the size of power of DG is much greater than the flexible load which has been limited to 30%. Moreover, the DR provides much more robust voltage support rather than the case without DR if the demand keeps increasing, and if the connection of DG increases. Then, the grid reinforcements could be postponed. Nevertheless, considering the costs to make the demand flexible, the economic relevance of the DR in the present case needs to be analyzed in more details with real costs.

VI. APPENDIX

Data of modified test feeder

Bus A*	Bus B*	Line type	r (Ω)	x (Ω)	b (S)	Load at Bus B	
						P(kW)	Q(kVar)
36	1		0	Xs**	0	0	0
35	1	240	1.6	1	3.6e-6	0	0
1	2	150	0.158	0.087	2.37e-7	930	370
2	3	150	0.106	0.058	1.59e-7	585	234
3	4	150	0.25	0.138	3.75e-7	585	234
4	5	150	0.354	0.195	5.31e-7	585	234
4	6	150	0.14	0.077	2.1e-7	585	234
6	7	150	0.22	0.121	3.3e-7	585	234
7	8	148	0.176	0.28	5.6e-9	371	149
8	9	148	0.02	0.031	0.63e-9	0	0
9	10	54	0.212	0.182	3.64e-9	232	93
9	13	148	0.682	1.085	2.17e-8	232	93
10	11	54	2.19	1.277	2.55e-8	232	93
11	12	54	2.52	1.47	2.94e-8	232	93
13	14	54	0.552	0.322	6.44e-9	232	93
13	15	75	0.114	0.091	1.82e-9	371	149
15	16	75	1.37	1.09	2.18e-8	371	149
16	17	75	0.07	0.056	1.12e-9	371	149
17	18	34	6.816	2.485	4.97e-8	232	93
17	19	75	1.232	0.98	1.96e-8	371	149
19	20	75	0.352	0.28	5.6e-9	232	93
20	21	34	0.24	0.087	1.75e-9	232	93
20	23	75	0.66	0.525	1.05e-8	0	0
21	22	34	3.072	1.12	2.24e-8	149	59
23	24	34	0.47	0.171	3.43e-9	232	93
23	25	54	1.068	0.623	1.25e-8	232	93
25	26	34	0.077	0.028	0.56e-9	149	59
25	30	54	0.077	0.028	0.56e-9	149	59
26	27	34	0.394	0.145	2.87e-9	149	59
27	28	34	1.056	0.385	7.7e-9	149	59
28	29	34	0.154	0.056	1.12e-9	149	59
30	31	54	0.492	0.287	5.74e-9	149	59
31	32	34	0.259	0.094	1.89e-9	149	59
31	33	34	0.087	0.031	0.63e-9	149	59
33	34	34	1.42	0.518	1.04e-8	149	59

*: A and B are respectively sending and receiving buses.

**: Xs is the short-circuit impedance of transformer

Line type: 150 or 240 mm² cabled, or 148, 75, 54, 34 mm² overhead

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