INFLUENCE OF GENERATOR CURTAILMENT PRIORITY ON NETWORK HOSTING CAPACITY

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ABSTRACT

Increasing penetration of distributed generation in distribution networks requires active constraint management to provide greater flexibility and use of existing network assets. Curtailing DG output under worse case scenarios to keep the network operating below voltage and thermal limits will play a major role in active network management. While a number of curtailment priority schemes are established there is a need to demonstrate the benefit of different priority schemes for curtailing multiple DGs. Comparing with 'first in last out' and other priority methods, this paper proposes and demonstrates that optimal setting of DG curtailment priority using multi-period OPF is not just technically appropriate but also economically beneficial. By extending this idea into the planning arena, the impact of curtailment management schemes on network hosting capacity is evaluated.

INTRODUCTION

In the transmission network, generation curtailment is an established methodology to tackle congestion. In passive distribution networks, curtailment is rarely used as the hosting capacity is largely determined by the 'worst-case' conditions, typically maximum generation and minimum demand. This guarantees the network can operate without any additional control requirement but it reduces the potential energy that can be harvested from distributed generation (DG). Given the infrequent occurrence of the worst case conditions, the introduction of active network management (ANM) can provide technical and economic benefits, and facilitate DG connections.

Operating for non-firm DG connections requires that the curtailment of multiple DG be governed by a set of priority rules that dictate the sharing of the curtailment between each DG. Current ANM systems such as the UK's Orkney scheme are operated on the 'first in last out' (FILO) rule where earlier connections will enjoy preferable treatment over later connections. A risk with FILO is that the last connection may be located at a network position where managing the output of DG has limited impact on relieving network constraints whereas the same voltage or thermal control effect could provided by other DG connections for less curtailment. Under certain conditions, inappropriate management schemes may reduce or 'sterilise' available hosting capacity for non-firm connections by over-curtailing production to uneconomic levels.

Several other curtailment priority schemes have been mooted including: 1) proportional reduction where all DG output is decreased equally and; 2) a 'technically most appropriate' approach where the minimum overall curtailment is delivered by curtailing the most appropriate DGs. Jupe *et al.* [1] and Zhou and Bialek [1, 2] use sensitivity methods to operate such schemes; however, these will not deliver truly optimal outcomes. Boehme *et al.* [3] analyse extensive renewable generation time series for both schemes: the proportional scheme is modelled using stepwise reductions using a load flow engine and the technically most appropriate reductions are determined by an optimal power flow (OPF) engine dispatching each DG up to the limits of the network based on equal (pseudo) costs for each renewable generator.

While the operation of an ANM with a known set of DG generators can be explored using time series simulation, planning connections to ANMs is highly complex. When a DG developer is looking to connect to an active network they will need to undertake very detailed assessments of the likely output of other generators and the resulting power flows in order to estimate their own likely generation and extent of curtailment. These values depend on the capacity of each generator, resource levels at each location, the technological and economic characteristics of the DG and any access rules governing operation of the ANM. The complexity of networks and competition for network access among developers makes this process extremely challenging. The process may be simplified using the network 'hosting capacity' as a guide.

The hosting capacity indicates the extent to which one or more DG may be connected across a network under specific conditions. A framework for analysing this for active networks was outlined by Ochoa *et al.* [4] using a multi-period OPF to determine DG hosting capacity for a series of ANM controls including curtailment. The analysis assumed controls would accommodate DG in the technically most effective manner and the extent of curtailment was limited to a pre-specified proportion of energy generation in order to avoid excessive curtailment and unreasonable volumes of capacity added. However, there was no explicit consideration of whether curtailment was economically viable nor did it cover other priority schemes.

In this paper the extent to which the financial viability of DG plants and different ANM access priority schemes affect network hosting capacity is outlined.

PROBLEM FORMULATION

Given the characteristics of the demand and variable distributed generation, the assessment of DG behaviour within active distribution networks presents several complexities when considering hosting capacity. The multi-period OPF developed in [4, 5] was adopted in the work to formulate the DG optimal planning and operational problem. The multi-period formulation is based around a process of describing a series of time periods m in which the coincidence of DG output and demand are similar.

The new development in this paper is the re-framing of the hosting capacity problem such that it is driven by the financial viability of each DG as determined by its capacity, the curtailment priority rules and the extent of curtailment. The hosting capacity is measured by maximising economic benefit:

$$\max \sum_{g\in G, m\in M} (P_g - P_{g,m}^{curt}) \times R \times M - C_{inv} - C_{om} \qquad (1)$$

where P_g is the capacity DG g and $P_{g,m}^{curt}$ is the extent of energy curtailment in period m summed across the whole time period M. The revenue for each DG is obtained from selling the energy produced R (which may include a subsidy as well as the wholesale price). The DG costs are a function of DG capacity: capital cost C_{inv} and operations and maintenance cost C_{om}.

The optimisation is subject to a range of basic network constraints: real and reactive nodal power balance; voltage level constraints; and thermal limits (lines and transformers). Different from the hosting capacity formulation in [3] which pre-defined constraints on the total amount of curtailed energy for each DG, here the economic performance acts as the constraint.

Three strategies for prioritising curtailment of multiple DG are considered in this work and embedded into the OPF framework:

1) ‘First in last out’ (FILO), where an extra constraint is added in the optimisation to ensure the preferable treatment of earlier DG connections (b) over later connections (a):

$$P_{a,m}^{curt} = \begin{cases} 0 & \text{if} \quad P_{b,m} > 0 \\ P_{a,m}^{curt} & \text{if} \quad P_{b,m} = 0 \end{cases} \qquad (2)$$

where, in period m, as long as the output of DG b ($P_{b,m}$) is not completely curtailed, there is no reduction in output of DG a ($P_{a,m}$).

2) Proportional curtailment, where all the DGs share the same percentage reduction to their production:

$$P_{a,m}^{curt} / P_{a,m} = P_{b,m}^{curt} / P_{b,m} \qquad (3)$$

3) Optimal curtailment setting (or technically most appropriate), where the reduction of each DG’s output is directly optimised by the OPF to maximise economic benefit. It is simple in the formulation since this control scheme excludes equations (2) and (3).

CASE STUDY

A typical rural section of a medium voltage distribution network with a radial topology and large R/X ratios is used as a case study It has been selected as it is simple to illustrate the effect of different curtailment schemes on hosting capacity analysis and offers potential to compare with results in [6]. The one-line diagram is shown in Fig. 1 and the line data is given in [6]. The feeders are supplied by one 31.5MVA 110/38kV transformer. The Grid Supply Point (GSP) voltage is assumed to be nominal and voltage limits are taken to be 10% of nominal. The maximum demand of the network is 15.12MW. The network has five potential locations at which new DG can be connected: buses gA, gB, gC, gD and gE in Fig. 1. To keep the illustration simple, all DG are assumed to operate at constant full output and to operate at unity power factor. The demand however varies with time as shown in Fig. 2 and is processed into a range of representative bins to reduce the computational burden. The optimisation of total hosting capacity is determined across the whole period (year). The DG economic parameters are given in Table 1.

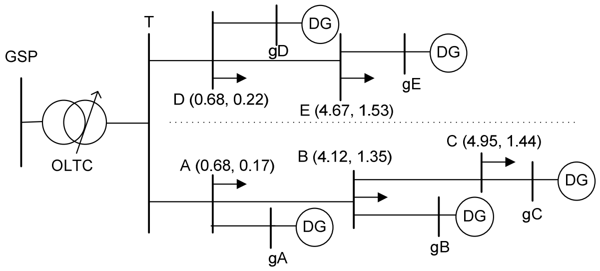

Fig. 1 Five-bus example network`

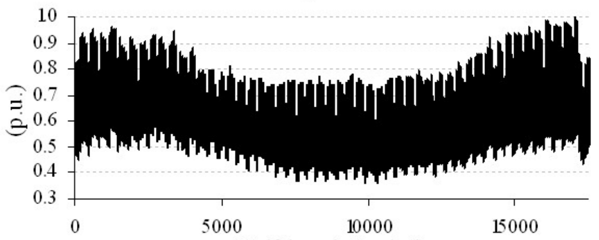

Fig. 2 Half-hourly demand data

Table 1 Economic parameters used in financial evaluation

Parameter	Value

Revenue from sales and support	£100/MWh
DG capital cost	£1000/kW
Annual operations and maintenance cost	£50/kW

The first analysis estimates the total capacity of the five DGs that can be accommodated in this network without any active generation management scheme being present. The results are given in Table 2 described by ‘Base’. This assumes a passive network without curtailment so the “worst-case” scenario when the coincidence of minimum demand and maximum generation occurs is the main constraint on capacity. The total capacity is 27 MW and the largest DG can connect nearest to the GSP (at location A) with progressively less towards the end of the feeders. Since the limitation on DG capacity is mainly imposed by the “worst-case” conditions, the curtailment of generation during these periods will alleviate the constraints (here voltage rise) allowing installed capacity to increase and overall energy production to rise.

The analysis was re-run for the different priority schemes. A set of four curtailment methods are examined:

1) FILO curtailment – assumption A: for each feeder, the curtailment is assumed to preferentially apply to DG that is further from the GSP (i.e. DG A is curtailed before B and B before C);
2) FILO curtailment – assumption B: for each feeder, the curtailment is assumed to preferentially apply to the DG that is nearest to the GSP (i.e. DG C is curtailed before B and B before A);
3) Proportional curtailment: all DG is curtailed equally;
4) Optimal setting curtailment: the objective is to maximise the total economic benefit obtained from all the DGs, as given in equation (1).

It can be seen in Table 2 that all studies that employ curtailment allow much more generation capacity able to be connected than the passive network analysis: the hosting capacity increases between 17 and 30%. With more capacity accommodated, curtailment schemes control production to guarantee the network operates below the voltage and thermal limits under low demand scenarios. However, the differences in curtailment between the four schemes and among the DGs are significant. The optimal curtailment setting delivers the largest overall capacity while FILO assumption A delivers the lowest. FILO assumption B and the proportional scheme sit in between. In each case DG A remains the largest generator but capacity increases of almost 50% are seen for other DG under some cases.

FILO assumption A favours DG located near to the end of the feeder. As such it results in smaller DG capacities overall with the two DGs nearest to the GSP being curtailed (i.e. A and D) while those further away are unaffected. This results in very significant curtailment of generator D (19%) but an 80% increase in capacity at generator D to boost generation. Overall, energy production rises by 12% from the base case. Curtailment at generator A is smaller – as it the increase in capacity. Under the proportional scheme all DG is curtailed equally by 7% with substantial increases in capacity (27%) and energy production (16%).

Optimal curtailment creates 22% extra production with 30% extra capacity, at the expense of 9% curtailment. All DG capacities are higher with most capacity increases coming from the DG at the end of the feeders. They however suffer higher levels of curtailment than under FILO assumption A. The level of curtailment of generator A is modest hence there is limited room to increase its capacity. It is notable that under this scheme the level of curtailment at all DGs other than A is higher than under proportional sharing. DGs B to E are all above the ~7% which is the best global reduction percentage obtained from the proportional curtailment scheme. The only exception is DG A, where four-fifths of its curtailment is avoided if other DGs are able to contribute more.

Although the process differs, FILO assumption B behaves more like the optimal setting scheme and favours DG capacity nearer the GSP. The curtailment of the DG at the very end of the feeders (C and E) is more severe than any other scheme but this allows overall production to almost match the optimal. The capacities of these two generators are allowed to increase to facilitate this.

Table 2 Comparison of DG capacity, production and curtailment under different curtailment priority schemes (OPT stands for the Optimal Setting Curtailment Scheme while PROP for the Proportional Curtailment scheme)

DG Location	Capacity (MW)					Energy (GWh)					Curtailment (%)				
	Base	FILO_A	FILO_B	OPT	PROP	Base	FILO_A	FILO_B	OPT	PROP	Base	FILO_A	FILO_B	OPT	PROP
DG A	15.0	16.3	15.2	15.6	15.8	131	138	133	135	129	0%	4%	0%	1%	7%
DG B	4.2	4.7	6.1	6.4	6.2	37	41	54	51	51	0%	0%	0%	9%	7%
DG C	3.0	3.1	5.7	5.5	4.7	26	27	38	42	39	0%	0%	24%	13%	7%
DG D	2.3	4.2	3.1	3.3	3.4	20	30	27	27	27	0%	19%	0%	9%	7%
DG E	2.4	3.4	4.5	4.3	4.1	21	29	32	33	30	0%	0%	18%	12%	7%
Total	27.0	31.7	34.6	35.2	34.2	237	266	284	288	276	0%	4%	8%	9%	7%

In terms of the net revenue that the DGs deliver, it can be seen from Table 3 that all curtailment schemes ensure more economic benefits from increased DG capacity. The benefits follow the energy production levels with the poorer performing FILO assumption A lowest, followed by the proportional scheme, with the FILO assumption B close to the optimal. The maximum net revenue is delivered by the optimal setting scheme with a 20.6% increase over the Base case, 5% above proportional curtailment and almost double that of FILO assumption A. It demonstrates that this advanced curtailment approach is not just technically efficient but also economically efficient.

Table 3 Net revenue for each curtailment scheme

Curtailment Scheme	Net revenue(£M)	Increase (%)
None	21.3	
FILO A	23.8	11.6%
FILO B	25.4	19.1%
Proportional	24.6	15.6%
Optimal	25.7	20.6%

DISCUSSION

The objective in this work was to examine how the choice of prioritising DG for curtailment in ANM systems would affect the hosting capacity. The results show that inappropriate choices of priority order – as may happen under FILO – can reduce hosting capacity compared to the optimal schemes. Although each scheme delivered benefits over passive networks, the implementation of the access rules also needs appropriate commercial arrangements and a policy framework to allocate the benefits among the DGs. It has to be fair for the DGs that contributed more in curtailment to deliver more revenue overall. This allocation method is of significance, especially in market environments where DNOs cannot own DG. The issue of fairness would be particularly important where DG has been connected on a firm connection basis and where reversion to non-firm operation would deliver substantial increases in output overall.

The DGs are assumed to be operated at unity power factor as a normal requirement, but this constraint could be easily relaxed. When the reactive power generation capability of DG is exploited, the OPF approach could be more feasible than the sensitivity method since both the active and reactive power have an impact on voltage constraints. Those two interactive factors are not easy to consider by linear simplification of sensitivity analyses.

Another constraint limiting the DG connection is overload of feeders, which is not fully illustrated in the case study. While sensitivity-based curtailment is considered effective to manage thermal congestion problem, it sometimes increases network losses. Due to the radial structure of distribution networks, DG located near to the overloaded line has a higher sensitivity. If this DG is curtailed first under a sensitivity based priority scheme, more losses will occur from the larger generation output elsewhere in the network. It would be logical to consider minimising losses and curtailment together, and therefore embedding DG curtailment control into multi-period OPF framework is more efficient since it can handle those two conflicting aspects simultaneously. It is also important to highlight that although the proportional curtailment scheme needs a constraint to represent the same percentage reduction among the DGs in optimisation formulation, the curtailment setting for each DG and each period is still optimised under this restriction. The difference between the considered schemes here is just limited to this additional control requirement.

CONCLUSION

In this paper, several ANM curtailment priority systems were examined for their impact on network hosting capacity. The hosting capacity evaluation method with curtailment management is extended to consider the economic benefits of active management. It was found that inappropriately chosen priority of curtailment resulted in reduced hosting capacity, lower overall energy capture and lower benefits from ANM. The approach would provide a basis for quantifying the economic incentives during the DG planning process.

REFERENCES

[1] S. C. E. Jupe, *et al.*, "Coordinated output control of multiple distributed generation schemes," *IET Renewable Power Generation,* vol. 4, 283-297, May 2010.

[2] Q. Zhou and J. W. Bialek, "Generation curtailment to manage voltage constraints in distribution networks," *IETt Generation Transmission & Distribution,* vol. 1, 492-498, May 2007.

[3] T. Boehme, *et al.*, "Assessment of distribution network limits for non-firm connection of renewable generation," *IET Renewable Power Generation,* vol. 4, 64-74, Jan 2010.

[4] L. F. Ochoa, *et al.*, "Distribution Network Capacity Assessment: Variable DG and Active Networks," *IEEE Transactions on Power Systems,* vol. 25, 87-95, Feb 2010.

[5] G. P. Harrison and A. R. Wallace, "Optimal power flow evaluation of distribution network capacity for the connection of distributed generation," *IEE Proc.-Generation Transmission and Distribution,* vol. 152, 115-122, Jan 2005.

[6] L. F. Ochoa, *et al.*, "Applying active network management schemes to an Irish distribution network for wind power maximisation," CIRED *2009.*