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INCORPORATING HARMONIC LIMITS INTO ASSESSMENT OF THE HOSTING CAPACITY OF ACTIVE NETWORKS

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ABSTRACT

Harmonic emissions from converter-interfaced distributed generation connection can potentially lead to voltage distortion levels that are above applicable standards. The risk increases as greater connection volumes are facilitated by Active Network Management schemes. By incorporating harmonic limits into assessment of the hosting capacity of active networks, this paper demonstrates that by incorporating harmonic levels at the planning stage can prevent inadvertent restrictions on the integration of renewables. Other aspects considered include: the impact of active network controls on harmonic propagation and hosting capacity and the role of active harmonic mitigation methods.

INTRODUCTION

Development of renewable distributed generation (DG) creates ongoing challenges for distribution network operators (DNOs). The problems of voltage rise and power flow (thermal) limits are seen as being manageable by active network management (ANM) schemes which promise to unlock new DG connections [1]. However, harmonic current emissions from power electronic converter-interfaced wind turbines are rapidly moving up the agenda of DNOs and developers. The scale of new DG connections enabled by active network management (ANM) means there is potential for harmonics to inadvertently place limits on the ability of distribution networks to accommodate DG.

Traditionally, harmonic studies in distribution networks focus on comparing harmonics and total harmonic distortion (THD) against standards such as the UK's Engineering Recommendation (ER) G5/4. Harmonic analyses are generally based on a well-developed network, in which generation capacity and load configurations are given and fixed. However, the rapid developments of DG make generation capacity a dynamic factor wherein DG volumes change substantially over the planning horizon. Existing harmonic simulation and filter planning methods may not be sufficient to address harmonic constraints in DG planning studies. It is proposed here that harmonic studies should be considered at the initial phase of planning, instead of being an afterthought following 'blind' DG development.

A multi-period AC optimal power flow technique has been previously applied to measure the distribution network hosting capacity under voltage and thermal constraints and with active network controls [1]. Here, it has been substantially extended to also take account of harmonic distortion limits. Harmonic power flow is then embedded into a harmonic-constrained optimal power flow (HOPF) model to ensure that individual harmonics and THD comply with the ER G5/4 standard.

A section of a UK generic distribution network is used as a case study. Several cases are examined. The first considers the hosting capacity of the active network without the harmonic constraints applied; subsequent assessment of harmonic propagation shows violations of statutory limits and impractical planned DG capacities when ANM is implemented. A second case enforces the harmonic standards resulting in reductions in hosting capacity.

PROBLEM FORMULATION

Harmonic Power Flow

Harmonic power flow analysis has been extensively used to study harmonic propagation in the network. The results of distortion level and voltage wave forms are useful to verify compliance with harmonic limits. Harmonic power flow can be presented mathematically as [2, 3]:

$$[V_h] = [Z_h][I_h] \qquad (1)$$

where $[Z_h]$ is the network impedance matrix; $[I_h]$ is the vector of nodal harmonic current injection of each bus; $[V_h]$ is the resulting harmonic voltage; and h is the harmonic order. Harmonic assessment using harmonic power flow can be separately conducted for every single DG applying for connection to the network. Modifying the DG capacity or installing expensive harmonic filters is necessary when the proposal violates harmonic limits. However, solutions deemed reasonable for each individual connection could deliver poor results for the network as a whole. For example, an early and minor connection may prevent development of other larger sites due to adverse harmonic propagation impacts, effectively reducing the total hosting capacity of the network or increasing the cost of additional filters. Given this network sterilisation effect, directly embedding harmonic power flow into initial DG planning techniques is a logical step and the focus of this work.

Harmonic Constrained Multi-Period Optimal Power Flow

AC OPF techniques have been proposed to find the hosting capacity of networks within given limitations and can guide DG planning to choose optimal connection location and capacity [4]. Similar to other physical constraints, harmonic limits can be incorporated into the OPF framework using results from harmonic power flow

by constraining THD and individual maximum harmonic distortion (IHD). The harmonic constraints are incorporated within an existing sophisticated multi-period AC OPF formulation [1] designed to determine hosting capacity whilst accounting for variability and coincidence of demand and wind generation as well as a suite of ANM controls. The objective function is given as follows:

$$\max \sum_{g \in G} P_g \qquad (2)$$

where P_g is the active capacity (MW) of DG connection g determined across a reduced time series (TS) analysis that groups wind generation and demand by a series of coincident ranges. This objective function is subject to a range of constraints which can be categorized into three sets: basic network limits; ANM constraints as well as the new harmonic distortion limits considered here. Fig. 1 shows the constraints structure for this proposed HOPF.
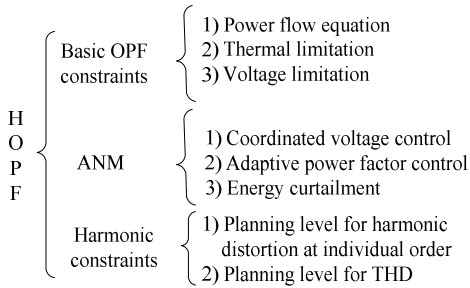

Fig. 1 Constraints within proposed HOPF formulation

1) Basic Network Constraint and ANM:
The allowable voltage at each bus and thermal rating for each branch in the network is ensured in every period by the thermal and voltage constraints. Active and reactive power balances are maintained by the power flow equation according to Kirchhoff's current law. A series of ANM controls are also embedded within the OPF formulation [1] to explore the capacity and harmonic implications of ANM. These are:
Coordinated Voltage Control (CVC): The transformer secondary voltage is dynamically set within upper or lower values to ensure more voltage headroom in the network.
Adaptive Power Factor Control (PFc): Many DG can operate at leading or lagging power factors and this control scheme dispatches the DG power angle for each period.
Energy Curtailment: The network characteristics and wind power pattern may necessitate curtailment of DG output in a given period to constrain voltage rise or power flows.
2) Harmonic Distortion Constraints
To provide the capability to constrain DG capacity and operation to ensure compliance with harmonic standards (ER G5/4-1), the following harmonic constraints apply:

$$V_{b,m}^h \leq IHD^{h,+} \qquad (3)$$

$$\frac{\sqrt{\sum_{h=2}^{H} (V_{b,m}^h)^2}}{V_{b,m}^1} \leq THD^+ \qquad (4)$$

where $V_{b,m}^h$ is voltage distortion at bus b for harmonic order h during the period m. $V_{b,m}^h$ can be obtained from the harmonic power flow equation (1). Constraints (3) and (4) guarantee that the HOPF defined DG volumes will comply with the harmonic standard.

Active Harmonic Filter
Should harmonics be above statutory levels filters can be used to mitigate them. The filters deployed in power systems can be classified into three categories: passive, active and hybrid. Conventional passive L-C filters are more economic [5] while active filters provide dynamic and adjustable compensation [6]. When it comes to the DG planning problem, there is a potential shortcoming with passive filters due to its power factor correction capability. The voltage rise problem can be (partly) mitigated by operating DG at lagging power factor [7] through absorbing reactive power. However, the capacitor installed within the passive filter will provide a local reactive source which will tend to worsen voltage rise. Given this, active filters are suggested here.
The most extensively applied active filter is the active power line conditioner (APLC). It is commonly modelled in filter planning areas as a current source injecting harmonics to its connection bus [8]:

$$I_{F,m}^h = I_{F,m}^{h,r} + jI_{F,m}^{h,i} \qquad (5)$$

where $I_{F,m}^{h,r}$ and $I_{F,m}^{h,j}$ represent the real and imaginary part of APLC current $I_{F,m}^h$ at bus m.

CASE STUDY

A generic UK distribution network is used here as a case study. Fig. 2 shows the one line diagram of this simplified EHV1 Network from the UK Generic Distribution System. Full data for this 16-bus 33-kV rural network are available in [9]. The feeders are supplied by two 30 MVA 132/33kV transformers. The Grid Supply Point (GSP) voltage is assumed to be nominal. Voltage limits are taken to be $\pm 6\%$ of nominal. A voltage regulator (VR) is located between buses 8 and 9, with the latter having a target voltage of 1.03 pu. The maximum demand of the network is 38.16 MW.
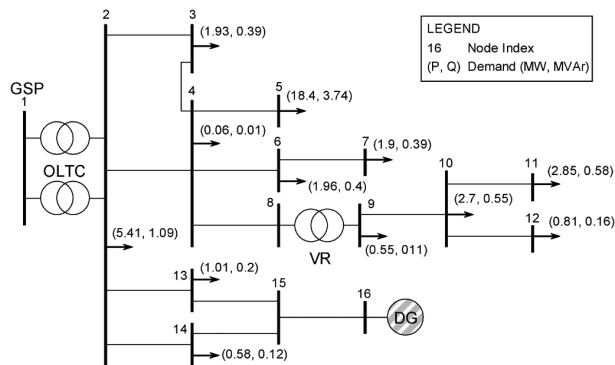
Fig. 2 Simplified EHV1 network [9] at maximum load

The network has one potential location (bus 16) at which new wind farms can be connected. For harmonic analysis, wind farms are modelled as current sources. The harmonic characteristics of a medium sized (0.6MW) wind turbine [10] are used for the analysis: Fig. 3 presents the frequency spectrum of maximum harmonic current where all triple harmonic orders (3rd, 6th, etc.) have been eliminated by the HV-MV transformer and all even orders cancelled since positive and negative parts of the current waveform are almost identical. In this paper, all harmonics from background nonlinear load is neglected due to the lack of data but this can be included effectively where detailed measurement or load models are available. It would be expected that distortion levels would tend to rise after considering background harmonics.
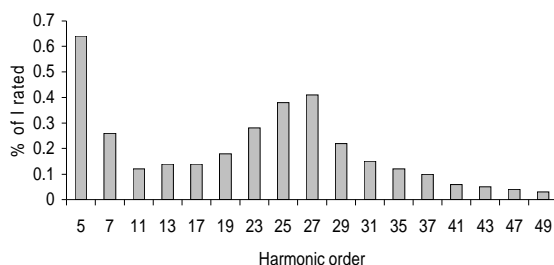

Fig. 3 Maximum harmonic current produced by wind turbine

Hosting Capacity and Harmonic Compliance

In this section, a series of analyses determine hosting capacity whilst ignoring potential harmonic constraints. Two snapshot analyses at maximum and minimum load are first considered, followed by the more sophisticated multi-period time-series (TS) analysis over the year. Following widely accepted practice, the wind farm at bus 16 is assumed operating at unity power factor. The results for these three analyses are shown in the first three columns of Fig. 4. It is clear that the DG hosting capacity from maximum load is identical to the whole year TS study while both are much lower than the minimum load case. This is very different from the commonly assumed 'worst case' scenario of maximum DG output at minimum load. The reason for this is that the relatively large load at bus 5 forces a high voltage setting at bus 2 limiting the voltage headroom for DG capacity elsewhere. This contrary

requirement will be worse at maximum load levels. Therefore, it is notable that the hosting capacity of this network is mainly constrained by the power flow transmitted to load at bus 5.
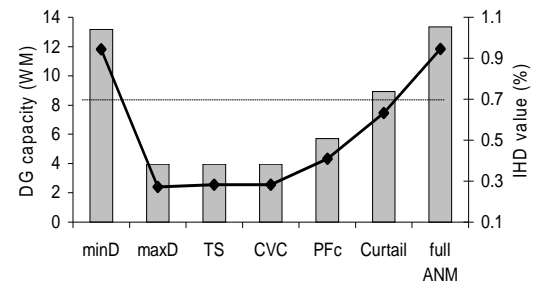

Fig. 4 DG capacity and IHD under different cases

The impact of ANM schemes on hosting capacity is now assessed using four different ANM combinations. The additional capacities after ANM implementation are shown in Fig. 4. The least effective technique for the network is CVC which has the same hosting capacity as the maximum load; this is unusual but demonstrates the conflicting requirements for the OLTC voltage control. PFc improves capacity levels by 45% by importing reactive power at low demand. Allowing wind to be curtailed by up to 5% over the year, sees selective reductions in DG production at low demand that allow hosting capacity to increase by 127%. After applying all the ANM, DG capacity slightly surpasses the result for the minimum load scenario (13.4 vs. 13.2 MW).

To consider whether the suggested hosting capacities are harmonically compliant, a series of harmonic power flow analyses were conducted. The THD in all cases shows compliance but the IHD of order 25 at DG bus 16 violates the requirement (0.7%) in the two high capacity cases (minimum load and full ANM). The IHD results are given as points along with the capacity column in Fig. 4. Due to the specific topology and loading patterns in this network that restrict hosting capacity, harmonics are not active constraints until higher levels of capacity and/or extensive ANM are applied. However, in general ignoring harmonics from assessments may result in harmonic non-compliance given the scale of new DG capacity enabled by ANM.

Analysis with Harmonic-Constrained OPF

With the initial OPF failing to comply with the G5/4 harmonic limits at higher capacity levels, obtaining a planning capacity within the distortion requirements will be vital in understanding the influence of harmonics on active networks. Applying the harmonic-constrained HOPF model using the same harmonic emission characteristics, a revised estimate for maximum DG capacity can be gained. The results are shown in Fig. 5. The 11.2MW DG capacity is a 16% reduction from the non-harmonically constrained result. The change is entirely the result of the harmonic constraints becoming

active and restricting the ANM-enhanced DG capacity down to maintain harmonic compliance. The worst IHD of the 25th order harmonic at DG connection bus under each capacity allocation are also presented in Fig. 5. It is clear that the results identified by the HOPF comply with harmonic limits (Fig. 5).
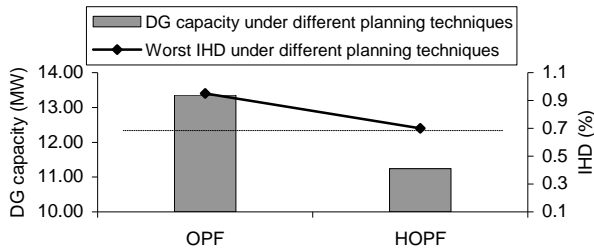

Fig. 5 DG capacity for ANM case under different constraint considerations

Mitigation With Active Filters

This reduction of DG capacity with HOPF reflects the potential value of introducing sufficient harmonic filter facilities, here specifically to treat the 25th order harmonic. To illustrate the influence of active filters a sequence of HOPF analyses were run for the full ANM case with the filter capacity increasing progressively from zero. Fig. 6 shows the impact of these active filters on the hosting capacity. It demonstrates that the hosting capacity initially increases linearly with filter size as larger filters offset more of the 25th harmonic. The leveling off of hosting capacity despite larger filters indicates that the harmonic constraint has become non-binding where other constraints dominate.
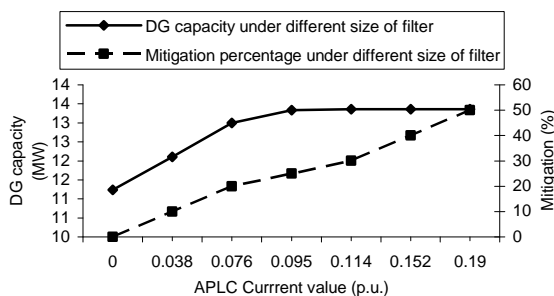

Fig. 6 Impact of different sized filters for full ANM case

CONCLUSION

In this paper, harmonic distortion limits are introduced as new constraints for the assessment of hosting capacity of active distribution networks to accommodate DG. A harmonic-constrained OPF provides additional information to guide DG developers and DNOs in maximising DG capacity. The harmonic propagation results following a time-series optimization suggest that violation of statutory harmonic limits and consequently impractical DG capacity levels occur when ANM 'frees up' sufficient new capacity. Directly incorporating THD

and individual harmonic planning level limits into the optimization of DG capacity sees a substantial reduction in connectable capacity. Based on the proposed HOPF techniques, potential harmonic mitigation solutions such as active filters are briefly explored in terms of their ability to free-up capacity. The cost of filter installation and maintenance should not be neglected, however.

Further work is required to evaluate the harmonic emissions from different DG technologies as well as the substantial increase in complexity that arises from handling multiple DGs and the influence of nonlinear loads in the distribution network. The HOPF formulation can be further extended to incorporate economic factors for the purpose of conducting cost-benefit studies.

ACKNOWLEDGMENTS

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