Distribution System Reactive Power Management Under Defined Power Transfer Standards

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Abstract **In light of high levels of distributed generation on distribution networks, voltage and reactive power management is challenging operators of both the distribution and transmission systems. The European network codes being developed by ENTSO-E are likely to call for "power transfer standards" to be defined, specifying the voltage and power factor bands which must be maintained at the transmission / distribution interface. This paper deals with how the DSO may meet such a power transfer standard as defined for nodes where there is significant wind generation connected on the distribution system. The work addresses the identification of the existing active and reactive power capability which could be achieved and a methodology for sizing and siting any distributed compensation required to deliver the desired characteristic in a manner which best meets utility priorities. The proposed methodology is tested on a network and the results discussed. Finally the characterisation method proposed is used to assess a number of alterative options which may reduce the requirement for compensation to be installed.**

I. INTRODUCTION

Distribution networks are increasingly hosting high levels of variable renewable generation (DG RES). In many European electricity systems, there is a prevalence of medium to large scale wind generation connected at medium and high voltages, presenting challenges in voltage management which can restrict the connectable capacity [1], [2]. Where active power cannot be curtailed, the import of reactive power is an established means of limiting voltage rise [3], [4], [5]. However this poses challenges as DG RES displaces conventional generation, potentially leaving limited sources of reactive power available [6], [7], [8].

The European Network of Transmission System Operators for Electricity (ENTSO-e) has been tasked by the European Commission to develop network codes to determine certain minimum requirements for the development and operation of European electricity systems [9]. While the codes pertain specifically to transmission networks, there will likely be conditions for interconnected systems including distribution systems, and DG RES above a certain capacity, regardless of connection to distribution or transmission systems. A key principle which has emerged through the development of these codes is the concept of "power transfer standards" between the distribution and transmission systems [10].

Analogous to the conditions required for the connection of any customer to the electricity system, these power transfer standards would lay out the requirements and profiles which the TSO and DSO would have to meet at transmission / distribution interface points. As a distribution system is a hybrid of demand and generation, its required power factor (PF) profile would likely be a hybrid of the requirements for demand (in Ireland within a power factor of 0.90 importing reactive power and unity) and generation (Figure 1).

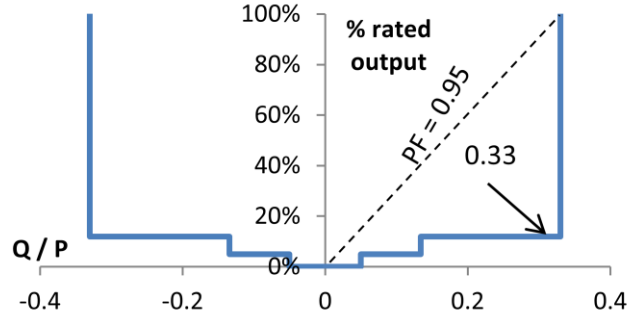

Figure 1: P/Q characteristic for wind farms >5 MW

A potential power transfer standard is illustrated in Figure 2. When drawing active power, the node is held to the same standard as a demand connection. Depending on network topologies, assets, demand and generation conditions, rated reactive power may not be available from distribution connected generation [11], but it is proposed that when a node is exporting active power it must be able to maintain a unity power factor. Additional reactive power resources may be required to meet power transfer standards in cases where wind generation is high – this work proposes a method to determine how such resources can be optimally planned..The proposed method develops on the investigation of the impact of DG RES in [12] and lays out a method for optimal location and capacity of any reactive power installations to meet a power transfer standard in Section II. The method extends the principle of reactive power management for loss

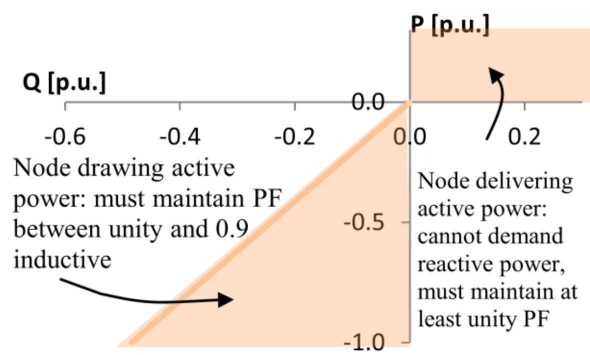

Figure 2: Proposed power transfer standard

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minimization or hosting capacity increases in operations as in [13] to its application at the planning stage. The method comprises an initial characterisation using AC Optimal Power Flow (OPF). Following this and based on the resultant characterisation and a defined power transfer standard, AC OPF methods are used to determine the optimal location and sizing of reactive compensation installations so as to allow for the best performance of the system subject to utility priorities. In Section III the method is applied to an existing network set in the Irish distribution system in the context of the power transfer standard proposed in Figure 2, with the results discussed in Section IV.

The primary utility priority addressed in the test application is hosting capacity maximisation, though the potential impact on losses of potential solutions are also presented. This informs a discussion of the impact of different objective functions on optimal capacity allocation. Finally in Section V the characterisation stage of the method is applied to asses a range of mitigating actions which could reduce the requirement for additional compensation.

II. METHOD

The proposed method is laid out in Figure 3 The steps labelled A form the characterisation stage and allow the most challenging conditions for meeting power transfer standards to be identified. The existing reactive power capability for a set of networks connected to a single transmission node may be determined as in step (i) using AC OPF with the objective function, reactive power as seen by the transmission system (q_{node}), both minimized and maximized to give the full characteristic.

$$max(\pm q_{node}),\ q_{node} = \sum_x q_{wf,x} + \sum_y q_{load,y} + \sum_z q_{loss,z} \quad (1)$$

In the above equation, x is the number of wind farms, y of load buses and z of network elements. Where there is diversity between the per unit output of each wind farm ("p_{wf}"), the lowest reactive power capability at any given combined generation level depending on the relative output of generators must be determined as in [15] There will be a different characteristic, a function of $\sum p_{wf}$, for each loading scenario so long as there is no deterministic correlation between load and variable generation.

Regardless of the intrinsic P/Q capability of any wind farm, the reactive power output of the wind farms (q_{wf}) may be limited by local network conditions. q_{node} is a function of the reactive power demands of generation, network voltage constraints, load and reactive power losses on the network. Δq_{max}, the maximum reactive power deficit found in step (ii) is an ideal indication of the maximum difference between the reactive capability indicated in the characteristic and the power transfer standard. The operational point (S) at which it occurs is the most challenging operational point from the perspective of meeting power transfer standards, thus the one which must be designed for. Graphically, on the P/Q plane, this is the point on the capacitive side of the characteristic which is horizontally furthest from a trace of the power transfer standard (e.g. Figure 2).

Step B aims to determine which locational combinations of buses will allow the minimum compensation capacities to be installed. This step is necessary to reduce the scale of the problem to that which is computationally feasible for networks of scale. AC OPF is used at operational point S for each combination of buses. The objective function which is minimised now becomes the combined capacity $\sum q_{comp}$ required to meet power transfer standards, installed at n buses.

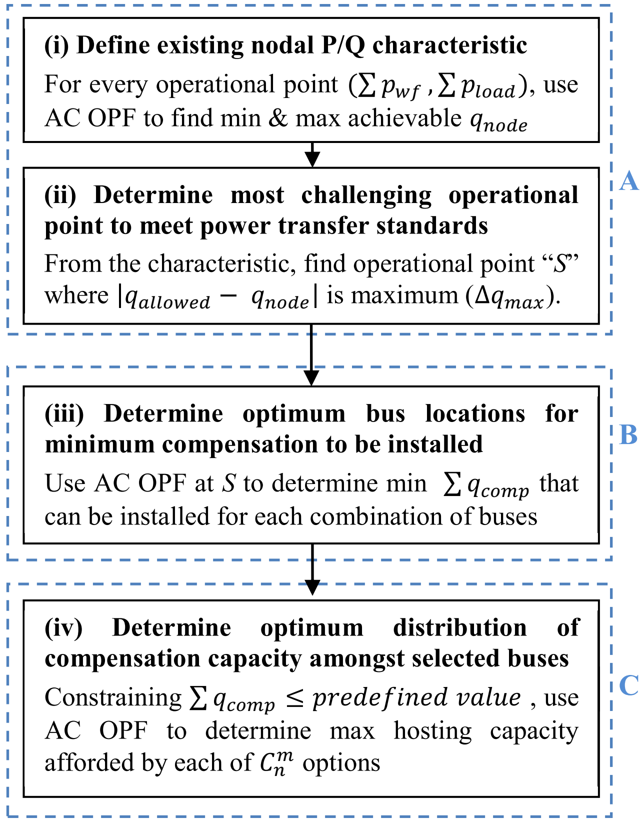

Figure 3: Proposed method

$$min(\sum q_{comp}),\ q_{comp} = \sum_n q_{comp,n} \quad (2)$$

The control variables are q_{wf} and the individual compensations installed at each bus ($q_{comp,n}$), giving a range of solutions.

Step C aims to determine the optimal distribution of compensation between buses. Those bus combinations which significantly lower $\sum q_{comp}$ identified in step B are further investigated to determine the optimal distribution of reactive capacity to meet predefined objectives. This can be achieved using AC OPF, again with control variables q_{comp} and q_{wf} though $\sum q_{comp}$ is now constrained to below a predefined value. This may be a little above the absolute minimum required to meet power transfer standards, if it is desired to afford greater influence to the q_{comp} control variables. The objective function for step C is a utility defined criterion, for example network hosting capacity or minimum distribution losses. Using multi-scenario OPF will allow the optimal solution across a range of likely or potential scenarios to be found.

$$max\left(\sum_{\text{scenario}} \sum_{\text{bus}} \text{hosting capacity}_{\text{bus,scenario}}\right) \quad (3)$$

Scenarios are different load and generation operating points which may allow for breaches of power transfer standards a small percentage of the time, or include firm connections only and combined firm and non-firm connections.

III. TEST NETWORK

The test network selected to apply the methodology is one in the northwest of Ireland, with high and growing variable wind generation. The network consists of ten 38 kV

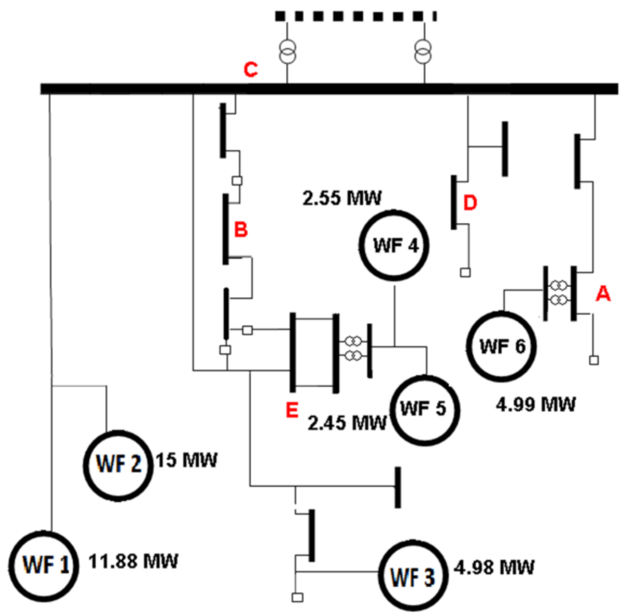

Figure 5: Test Network

distribution sub stations with a combined peak load of 65.56 MW and a summer valley minimum load of 16.94 MW. The total installed wind capacity at present is 40.31 MW, distributed across six locations, three at 20kV and three at 38 kV. With a further 46.70 MW of generation soon to be connected, giving a total of 87 MW or generation capacity at 133% of the peak demand, this set of networks often serves to inject power into the transmission network. The network is illustrated in Figure 5.

The wind farms at 38 kV are taken to have the capability in Figure 1. All installations at 20 kV are modelled operating at a constant power factor of 0.95 inductive. The measured generation profiles reveal that they have a highly correlated output once cut in speed has been exceeded, likely due to their location within a 16 km radius. The measured loading profiles are also highly correlated, following a deterministic pattern, and have an approximate power factor of 0.95 lagging. Only 0.07% of the time is the loading below 25% or above 90% of peak. Through binning and discretization of load profiles, thirty loading scenarios were derived to represent the loading range of these networks.

Voltage bands for each bus are as per the Irish Distribution Code. The network was modelled in the AIMMS optimisation environment using the operational tool outlined in [14] but with the characteristic of wind farms altered to that described in [15]. The tool was developed to include a constraint representing the power flow transfer to be met, to allow for multi-scenario analysis, for selected wind farms operating at a constant power factor and to include reactive compensation plant models. The power transfer standard used for this test case was the one proposed in section I

IV. RESULTS AND DISCUSSION

A. *Characterisation stage*

The existing characteristic was determined at a broad range of representative loading levels (including those in III and at maximum loading), as a function of $\sum p_{wf}$, in 1% (~0.4 MW) steps. Figure 6 illustrates the characteristic at maximum and minimum load, with the trend the characteristic follows with load variation shaded superimposed on the power transfer standard. Operational point S identified is at maximum generation but with sufficient load that the networks still import active power, with a reactive power deficit of 13.68 MVAr.

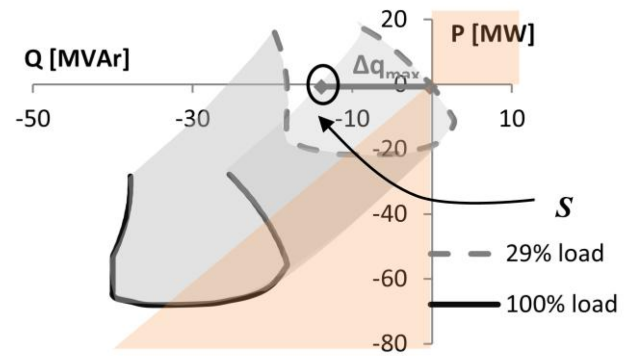

Figure 6: Existing power transfer characteristic

The full reactive capability of wind farms 1 and 2 cannot be delivered at high output due to local voltage rise (see Figure 5 – at point A, just 41% of full active power output, only reduced reactive power can be delivered. From point B, at 66% output reactive power must be drawn to manage local voltage rise. This increases the nodal Δq significantly as wind farm output increases, resulting in the sharp incline in the

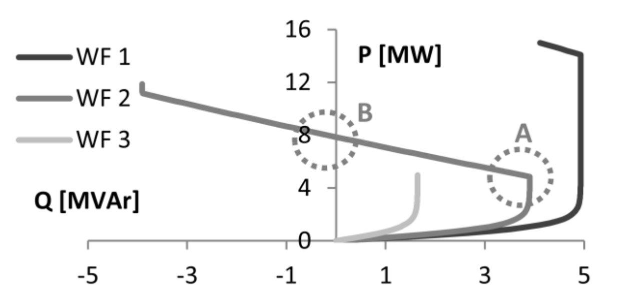

Figure 4: Individual reactive capabilities of 38kV wind farms

characteristic, most notable at minimum load (Figure 6)

B. *Location of buses for compensation installations*

There are a total of 12 utility owned buses on the network at which reactive power compensation could be installed and for this test case, a total of 3 installations are to be made. For each of the 165 combinations of 3 buses from 12, AC OPF at operational point S was run applying the nodal power factor constraint, but with unlimited reactive compensation installed at each of the 3 buses. Following Step B in Figure 2, the control variables were q_{comp} at each of the 3 buses and q_{wf} of the 3 wind farms on the 38kV network. This resulted in

165 solutions of which those including buses A, B, C, D and E in Figure 5 allowed significantly lower total $\sum q_{comp}$. The worst performing solutions were those including some or all of the most peripheral buses, with little local load

C. Optimal compensation capacity distribution

The criterion selected for optimisation was maximum generation hosting capacity on the 38 kV network. The network was modelled with new installations connected to each 38kV bus, each with an unlimited active power output ("p_{ng}") but adhering to the reactive capability illustrated in Figure 1.

Multi-scenario analysis was applied so as to determine the solution which best balances a design to meet uncertainty over certain network parameters or regulatory developments. It is as yet unclear whether nodal power transfer standards must be met 100% of the time, or whether deviation would be allowed a certain amount of the time at a marginal cost. Planning for this is primarily a consideration of generation rather than load. The existing characteristic results in *S* at the point where $\sum p_{wf} \approx \sum p_{load}$. However once the installed generation is significantly higher than the peak load,, *S* will be that at maximum demand and maximum generation and Δq_{max} will almost entirely comprise wind farm reactive demand. In this case planning to meet nodal power transfer standards 90% of the time becomes analogous to planning to meet the reactive power demand when wind generation is at the maximum level within which it remains 90% of the time. In the case of these networks, 90% of the time generation is at or below 83.95% of maximum output.

Additionally, while only firm access is at present permitted by regulatory policy, it may be prudent to allow for higher capacities of not just firm but non-firm generation if there is an expectation that the regulatory position may change. This being the case, the model includes scenarios where generation is modelled at both minimum and maximum load. This gives a total of 4 scenarios: Scenarios 1 and 2 are at max load and Scenarios 3 and 4 are at min load. Scenarios 1 and 3 require 100% adherence to power transfer standards but scenarios 2 and 4 allow for deviation 10% of the time. With 4 scenarios (*s*) and 5 buses (*m*) equation (3 becomes $max\left(\sum_{s=1}^{4}\sum_{m=1}^{5} p_{ng\ s,m}\right)$.

The results for 4 examples of the bus combinations are in Figure 8. For each combination of buses (ABC, ABD, ABE, ADE) the hosting capacity facilitated under each scenario is shaded and indicated. There is little variation in the hosting capacities offered by many bus combinations, though different solutions cater better for the particular scenarios. For example while solution ABC would afford over twice the hosting capacity of ABD across all scenarios, they offer almost identical hosting capacity under Scenario 4. Annual loss estimates ranged from 6.63 MWh to 6.90 MWh In Figure 8 we can see that combinations ABE and ADE offer similar hosting capacities, however ABE results in 160 MWh lower annual losses.

In step B of the method, the objective function was minimum $\sum q_{comp}$ whereas in step C it was maximum hosting capacity, though the same control variables were available. For two bus combinations, ABC and BCE, Figure

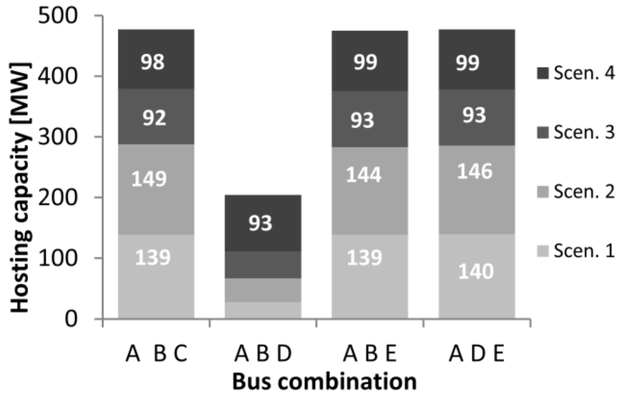

Figure 8: Results of Step C for 4 bus combinations

7 illustrates the difference in capacity distributions depending on objective function. For buses ABC, a relatively even distribution of compensation installed at each bus offers the minimum total compensation required (Step B), whereas in Step C we find that the solution which offers the greatest hosting capacity is achieved when 12.65 MVAr (90.36%) is installed at bus B. Similarly for bus combination BCE, in Step B 8.34 MVAr is allocated to bus C but from Step C we

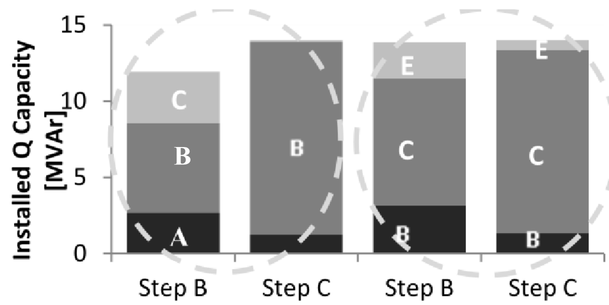

Figure 7: Redistribution of reactive compensation from Step B to Step C for 2 bus combinations

see that allocating 12 MVAr (85.71% of the total compensation) to bus C better meets the objective function of maximum total hosting capacity.

V. ALTERNATIVE OPTIONS FOR NETWORK PLANNING

Lower levels of compensation could be required if certain network parameters were modified. As a principle this is illustrated by the local voltage limited reactive output of wind farm 2 (see Figures 5 & 6), a function of the voltage rise which is affected by network impedances, and the allowable voltage at the wind farm site.

D. Network asset impedances

The impact of network impedances may have a significant impact on the compensation required, be this through lower resistances reducing the voltage rise thus allowing a higher reactive power export, or through lower network reactances resulting in reduced reactive losses. The network was modelled under two reinforcement scenarios, (i) lines of networks connecting wind generation uprated to a higher capacity / lower resistance and (ii) transformer reactances reduced by 20%. These resulted in the characteristic being stretched towards the positive Q half of the P/Q plane (as illustrated for the characterisation with lower reactance transformers in Figure 9 with Δq_{max} reduced from 13.68 MVAr to less than 5 MVAr.

While these results are require significant reinforcements or replacement of large HV transformers, they indicate that there could be value in strategic reinforcements or assessing the additional cost in reviewing specifications for future transformers to be installed.

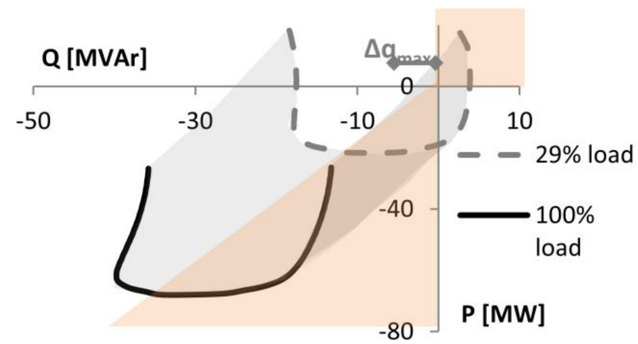

Figure 9: Power transfer characteristic with reduced transformer reactances

E. Relaxation of voltage standards at wind farm connection points

Applying Step A of the method but relaxing the upper voltage constraint by 10% at dedicated generation connection points produced a characteristic similar to that in Figure 9. This time the stretch to the positive Q axis was due to an increased capability of wind farms to deliver reactive power, as illustrated in Figure 10.

However it should be noted that this is at the cost of potentially sterilising these network points from future demand connections. It would likely increase the reinforcement required and thus cost of future wind connections on the network, as the existing hosting capacity afforded by voltage rise would have been allocated to allow the export of reactive from existing generation rather than being reserved for active power from future generation connections.

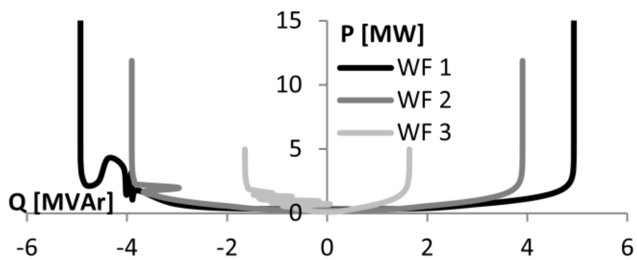

Figure 10: Reactive capability of individual wind farms with voltage standard relaxed

VI. CONCLUSIONS

This work presents a characterisation and planning method which would allow a utility optimally plan to meet “power transfer standards” at the TSO / DSO interface. The characterisation stage allows a visualisation of the existing power factor profile at the TSO node feeding a set of networks, then the planning stage aims to optimally size and locate reactive compensation to meet the power transfer standard. The method was tested on a network which is a likely candidate for the application of such power transfer restrictions. The characterisation illustrated the reactive power deficit relative to a likely power transfer standard for the network and the impact of local voltage restrictions on the contribution of wind generation to the nodal characteristic. The planning stage illustrated that

- the location of buses on a network with compensation installed will impact the total compensation required
- for any set of buses, the optimal distribution of compensation installed will depend on the objective function
- the distribution of reactive capacities will have a direct bearing on network losses or hosting capacity

Finally it was illustrated that the characterization method can be applied to investigate the impact of network asset and operational standards on the power factor profile thus on the total compensation required.

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