MAXIMISATION OF INTERMITTENT DISTRIBUTED GENERATION IN ACTIVE NETWORKS

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ABSTRACT

Worldwide interest in renewable energy combined with technology advances has increased the connection of intermittent distributed generation to distribution networks. To allow maximum penetration of such developments without compromising the normal operation of the network requires several technical issues to be assessed. In this context, active management of the network, i.e., the integration of assets and network participants through the real-time use of control and communication systems, will play a major role. This paper proposes a multi-period steady-state analysis for maximising the connection of intermittent distributed generation through an optimal power flow-based technique adapted for active network management. A medium voltage distribution network is analysed considering different loading levels and discretised wind power outputs over a year. Results are presented and discussed.

INTRODUCTION

Driven by environmental and fuel security concerns, governments worldwide have set targets to diversify their energy mixes in the forthcoming decades. It is certain that renewable technologies will continue to have incentives to increase their connection to distribution networks. In this scenario, Distribution Network Operators (DNOs) need several technical issues to be evaluated to allow the proper accommodation of high penetration levels of Distributed Generation (DG) [1]. Moreover, the intermittent characteristics of renewable technologies like wind power make it important to also include time-varying analyses when evaluating the distribution system performance [2, 3]. The benefits of using real-time control and communication systems to better integrate and exploit the different network assets and participants have been discussed from both the technical and economic points of view in the last decade [4-6]. While it is certain that the actual adoption of active network management by DNOs will strongly depend on the regulatory framework and, consequently, on its profitability, high DG penetration studies must consider this approach to better manage and accommodate more developments.

The ‘fit and forget’ approach used historically for the connection of new generation might lead to the sterilisation of the network’s ability to connect further capacity [7]. Therefore, evaluating the network’s maximum DG capacity is important to provide distribution engineers with alternatives in decision making and to estimate the investments required to allow the connection of further generation capacity. From the transmission network point of view, given the lower costs for developers to connect to distribution systems, an overall assessment of the maximum generation that might be delivered upstream is also critical to evaluate the necessity of future reinforcements, or alternatively, to identify areas where DG deployment should be constrained.

In this work, a multi-period steady-state analysis is proposed for maximising the connection of intermittent DG through an optimal power flow (OPF)-based technique. Here, an active network scenario is envisaged where the tap changing capabilities at the substation and energy curtailment are used as means to allow maximum absorption of wind power while respecting voltage statutory limits, loss limits and physical constraints such as thermal limits and fault levels.

A medium voltage distribution network considering different loading levels and discretised variability of wind power generation is analysed over a year. Results are presented remarking the advantages of the multi-period OPF-based methodology and the role of active networks in allowing further penetration of wind power developments.

OPF AND ACTIVE NETWORKS

Given network characteristics such as capacity headroom, fault levels, losses, topology, demand behaviour and potential locations for developments, DG capacity allocation presents several complexities when considered as an optimisation problem. The approach considers the non-linear programming (NLP) formulation of a multi-period OPF tailored to determine the maximum DG capacity able to be connected to a given network. The varying characteristics of the demand and wind generation will be taken into account in form of loading and power output levels, respectively. The multi-periodicity is achieved by relating each demand-generation combination to its time duration. In this way, each period has a different set of power flow variables whereas a unique set of generation capacity variables is used throughout the analysis in order to create the multi-period interdependency.

The basic OPF formulation aimed at maximising the total DG capacity P across n generators (indexed by g) is

$$\text{Maximise} \sum_{g=1}^{n} P_g \tag{1}$$

subject to:

- real and reactive nodal power balance
- voltage level constraints
- voltage angle set to zero for the reference bus
- thermal limits (lines and transformers)
- constant power factor operation of DG units (included in the nodal power balance equations)

Through an active network management approach, DNOs will be capable of optimising the use of their assets by dispatching generation, controlling transformer on-load tap changers and voltage regulators, managing reactive power and reconfiguring the system [4-6, 8]. Therefore, in addition to network constraints traditionally used in OPF formulations (e.g. voltage and thermal limits), variables and constraints derived from active network management schemes and other technical-economic constraints will also need to be incorporated in the approach. The following subsections describe some of the considerations.

Co-ordinated Voltage Control

By controlling the on-load tap changers at the substation, and, consequently, the corresponding voltage of the busbar, depending on the loading level, more DG capacity might be connected [5]. Thus, the voltage at the substation will be treated as a variable, rather than a fixed parameter, while maintaining the resulting value within the statutory range.

Energy Curtailment

High penetration of DG could result in increased voltages, mainly at times of minimum demand. Particularly, for non-conventional generation with intermittent behaviour, curtailment of the power output is an option to alleviate such problems [5, 9]. Power curtailment is formulated here by adding an extra variable, to act as a negative generation (or positive demand) at the same location of a given DG unit. Additionally, considering that the financial costs of lost wind power production will limit the use of this scheme, in the proposed formulation the total amount of curtailed energy will be restricted to a percentage of the total energy that otherwise would have been delivered through each DG connection.

Losses

Although DG may unload lines and reduce losses, the reverse power flows resulting from high penetration levels can give rise to excessive losses. Given the regulatory framework commonly applied to DNOs, with respect to technical losses, an increase of standard losses would result in economic penalties. Thus, assuming an active network scenario where losses still play a significant role, total energy losses will be constrained in the proposed OPF formulation.

Fault Levels

Fault level studies are mandatory to assess the feasibility of DG developments. Given the relatively limited short-circuit capacity margin commonly found in (urban) distribution networks, new generation capacity might be limited. While wider use of power electronics is expected to reduce fault level contributions from DG [10], current technologies, mainly for wind power generation, still require special attention [11]. In this work, fault levels will be included in the OPF as a constraint. Rather than the computationally intensive direct incorporation of such constraints [12], for simplicity, DG fault contributions are considered to be linearly dependent on their rated current [11, 13].

Given the typical radial arrangement of distribution networks, the maximum fault level will be obtained when considering a three-phase fault at the busbar of the substation. Thus, the initial symmetrical short-circuit power at the busbar resulting from the contributions of both the upstream grid and total DG capacity, will be limited to the design short-circuit capacity of the network. Since the IEC 60909 Standard will be adopted for the corresponding calculations, the rated voltage at the busbar will affect the final contribution of the upstream grid [11].

CASE STUDY

In this section the application of the OPF-based technique to a test distribution network will be presented.

69-bus network

The technique was applied to a 69-bus 11 kV radial distribution system [14]. The network one-line diagram is shown in Fig. 1.

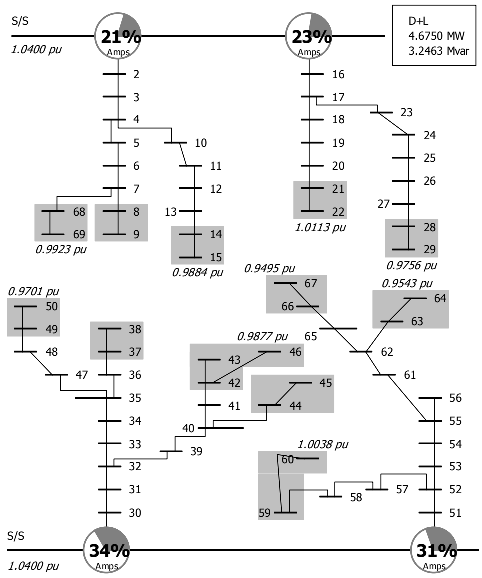

Fig 1. 69-bus network one-line diagram. Power flow results considering peak load (see Table 1). D+L: Total demand plus system's line losses. Pie charts illustrate the maximum capacity usage of the line sections.

It is assumed that the four feeders are supplied by two identical 10 MVA 33/11 kV transformers operated in parallel with a reactance of 10%. Voltage limits are taken to be ±6% of nominal and feeder thermal limits are 5.1 MVA (270 A/phase). The complete network data are given in [14]. The short-circuit capacity of the system at the primary side of the transformers is considered to be 1000 MVA. The design short-circuit capacity for the 11 kV network is 250 MVA. As recommended by the IEC Standard, the R/X ratio for the corresponding equivalent impedance is 0.1, and the voltage factor, which accounts for variations of the system voltage, is taken as 1.1 [11]. Load losses for the substation's transformers are not considered.

The computational burden of a detailed time-series analysis (e.g. 15-minute, hourly) is managed by using a simplified load duration curve with discrete generation levels, as will be explained in the following subsection.

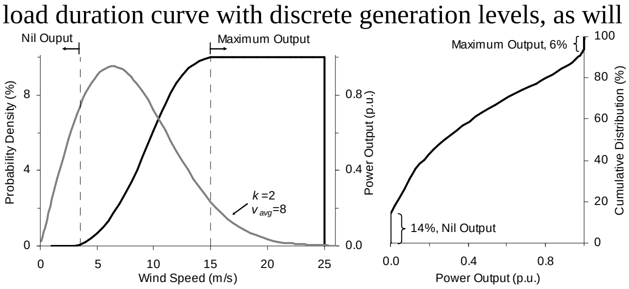

Fig 3. (Left) Weibull distribution and wind turbine power curve. (Right) Cumulative distribution of wind power output.

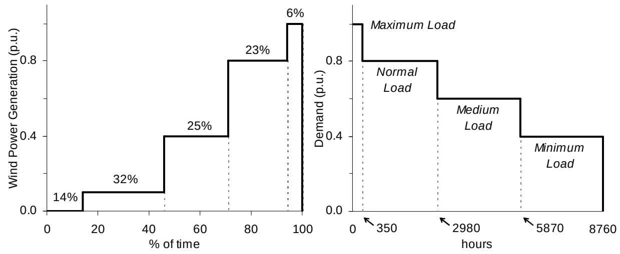

Fig 4. (Left) Wind generation levels. (Right) Load duration curve.

Intermittent Generation and Demand

In order to capture the time duration of various wind power outputs the Weibull probability distribution was utilised for a mean wind speed of 8m/s, plotted in Fig. 3, along with a typical wind power curve. The cumulative distribution function obtained with the adopted parameters and power curve is also presented in Fig. 3.

With the cumulative distribution it is possible to approximate the time duration of different generation levels. The adopted discretised wind power outputs are shown in Fig. 4 (left), which will be analysed for each band of the load duration curve (Fig. 4, right). Accordingly, twenty combinations, i.e., periods, of demand-generation will be considered here. The demand at each node of the network is assumed to follow the load curve in Fig. 4. The characteristics of the adopted loading levels are given in Table I for a year.

Table 1. Characteristics of adopted loading levels (1 year).

Load Band	% of Time	Duration (H)	Active Power (MW)	Reactive Power (MVAr)	Losses (MW)
Minimum	33	2890.8	1.7868	1.2236	0.0309
Medium	33	2890.8	2.6802	1.8354	0.0712
Normal	30	2628	3.5736	2.4472	0.1296
Maximum	4	350.4	4.4670	3.0590	0.2077

Maximising Intermittent DG Capacity

As shown in Fig. 2, the end nodes of each feeder correspond to potential locations for wind power developments, representing the connection of DG in rural areas of the network. The following assumptions are taken into account for the analyses:

- DG units operate at 0.9 leading power factor (producing reactive power).
- The substation power exports to the upstream grid are limited to the capacity of one transformer (10 MVA).
- Energy curtailed does not exceed 10% of the total potential wind energy production (of each DG unit).
- DG fault level contribution is 5 times its rated current. Experience proves that this value can be used for roughly consider wind turbines not connected via power electronic converters [11, 13].
- Annual losses for the DG scenario do not exceed those obtained for the non-DG configuration (708 MWh).

The proposed OPF was coded in the AIMMS optimisation modelling environment [15].

Initially, the potential gains from a co-ordinated voltage control (CVC) scheme are investigated. As shown in Fig. 5, it is clear that a passive strategy with fixed substation voltage ($V_{S/S}$=1.04pu), limits the network's ability to connect new generation capacity. Indeed, considering CVC the maximum DG capacity is 3.4 times that for fixed substation voltage, resulting in an increase of production of wind energy from 11.8 to 40 GWh. However, while the latter is does not exceed the fault level limits, the larger short-circuit contributions from the larger penetrations possible with CVC exceed the 250 MVA fault level limit by 7%. In addition, the CVC case results in annual energy losses that are 3 times those of the original configuration (no DG). In terms of capacity usage of the lines, the CVC approach increased the maximum value from 35% to 75%. As for voltages (weighted average based on time duration), lower values were mostly used by the CVC in order to accommodate further generation capacity. This resulted.

When the wind energy curtailment scheme is also incorporated within the OPF (CVC+Cu), the resultant DG penetration is even higher: 4.2 times the maximum capacity without active management, or 24% increase on the CVC case. Nonetheless, the design short-circuit capacity of the network is surpassed by 11%.

The use of co-ordinated voltage control considering energy loss limits (CVC+Lo), as expected, results in lower generation capacity than the CVC case. However, it provides a DG deployment that complies with the fault level limits.

Integrating the previously analysed schemes while limiting the energy losses results in 2.7 times the passive network capacity (see Fig. 6, CVC+Cu+Lo). Again, the fault level limit is violated. On the other hand, assessing the maximum DG capacity based solely on voltage control and fault levels (CVC+FL) provides a larger penetration, but at a cost of exceeding the loss limit.

The full integration of the active network schemes and the technical-economic constraints proposed here leads to a maximum DG capacity of 10.5 MVA, with 38% maximum capacity usage of lines, 1.03pu average substation voltage, and 28.3 GWh of delivered wind energy. Compared to the maximum generation capacity obtained through a passive network approach, the proposed methodology shows that

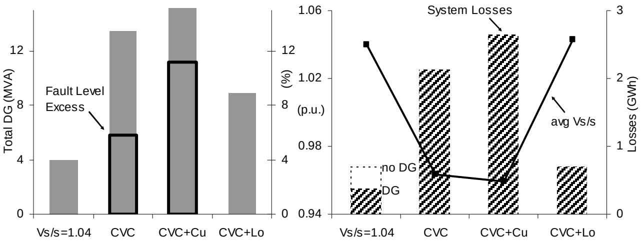

Fig 5. Maximum DG capacity (left) and network characteristics (right) for passive scheme ($V_{S/S}$=1.04pu) and active network schemes: co-ordinated voltage control (CVC), wind energy curtailment (Cu) and loss limits (Lo).

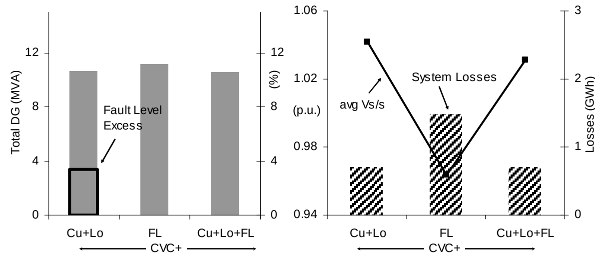

Fig 6. Maximum DG capacity (left) and network characteristics (right) for active network schemes: co-ordinated voltage control (CVC), wind energy curtailment (Cu), loss limits (Lo), and fault levels (FL).

the studied system is actually able to connect 2.6 times more, while respecting voltage, thermal, fault level and loss limits

It is indeed during the worst demand-generation scenarios (e.g. min-max, max-max) where significant penetration constraints may be found. However, considering the variability and duration provides a more detailed picture of the network's capabilities and weaknesses.

CONCLUSIONS

It is certain that location of new generation capacity will depend on land availability. As for renewables, on top of land issues, good source availability is also a major concern for the economic feasibility of a development. However, understanding the capabilities of the networks considering certain strategies to optimise the intake of DG is important for DNOS from both technical and commercial points of view. The OPF technique presented here can also be extended to study the locational benefits of DG in order to provide guidelines on the creation of connection incentives.

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