OPTIMAL ALLOCATION OF EMBEDDED GENERATION ON THE IRISH DISTRIBUTION NETWORK

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INTRODUCTION

As a result of the restructuring of electricity markets and the targets laid down for renewable energy, increasing amounts of Embedded Generation are being connected to distribution networks. To accommodate this new type of generation the existing distribution network should be utilised and developed in an optimal manner. This paper explains the background to the technical constraints faced by EG projects and a methodology using linear programming to determine the optimal allocation of EG with respect to these constraints is demonstrated. The methodology is implemented and tested on sections of the Irish distribution network. Results are presented demonstrating that the proper placement and sizing of EG is crucial to the accommodation of increasing levels of EG on distribution networks.

EMBEDDED GENERATION

Embedded generation (EG) can be defined as small-scale generation, which is not directly connected to the transmission system and is not centrally dispatched. It is a mixture of renewable and conventional energy sources - wind, small-scale hydro, combined heat and power (CHP), photovoltaic and landfill gas. In Ireland this generation is typically connected at 38kV or MV (10/20kV). The vast majority of applications for connections coming into the distribution network operator (DNO) are wind farm projects. The introduction of EG has lead to changes in the characteristics of the network, such as reversed active and reactive power flows and increased short circuit levels. If increasing levels of generation are to be accommodated, then there must be a change of thinking regarding the planning and design of the distribution network.

There are increasing calls for the development of the distribution network from a passive network to an active one in order to facilitate increasing levels of embedded generation [1]. It has been stated that there will be a large investment in the distribution network transforming it from a passive to an active network. If this is to be the case a number of steps should be followed. Firstly, best use should be made of the existing distribution network by optimal allocation of EG. Secondly, the development of the distribution system should be planned optimally with all relevant considerations taken account of. The placement of generation on a first come first serve basis invariably limits the overall capacity of embedded generation [2]. A methodology has been developed to determine the suitable locations and ratings for EG on distribution networks with respect to the technical constraints, which will enable an optimal penetration of generation on the network and avoid network sterilisation [3]. Network sterilisation results when capacity is allocated to the bus/buses whose voltage and/or short circuit levels are most sensitive to power injections. Thus no more generation can be connected as the buses are constrained.

The methodology detailed in [3] exploits the interdependence, if any, of the buses with regard to the constraints. The constraints all have either linear or approximately linear characteristics with respect to increasing power injections. The methodology determines the optimal allocation with respect to all of the relevant technical constraints.

The technical constraints on EG are outlined in the following section. Sections of the Irish distribution network are modelled in DIgSILENT Powerfactory using network data obtained from the distribution network operator (DNO). The methodology is tested on a number of sections and results are shown, which illustrate how network sterilisation is avoided if EG is optimally allocated. Optimal allocation ensures best use of the existing assets and achieves a higher penetration of EG in a cost effective manner.

TECHNICAL CONSTRAINTS

An optimal allocation of embedded generation exists for each section of the existing network. Generation capacity should be allocated across the buses such the capacity is maximised and none of the technical constraints are breached.

Thermal Constraint

This is a stand alone constraint, simply put the rated current of the lines must not be exceeded. Under standard voltage levels and power factor conditions the rated current of the line can be translated directly into a rated active power for that line.

Equipment Ratings

Transformer Capacity. The rating of the transformer at the higher voltage level must be considered. The amount of generation connected minus the summer valley load must not exceed the rating of the transformer. If there is some existing generation then this must be subtracted from the total, given that only firm access is currently offered on the distribution network. The result is the remaining capacity available at that station. In the case of two parallel transformers, the capacity is taken as the rating of the smaller transformer plus the summer valley load.

Short Circuit Level. A maximum short circuit rating for all equipment is laid down in the distribution code [4]. A short circuit calculation is carried out to ensure that this constraint is not exceeded as the level of installed capacity increases. The short circuit level (SCL) is highest at the transmission system bus. Buses close to this bus may find their capacity limited as a result.

Short Circuit Ratio

The short circuit ratio (SCR) is the ratio of generator power to the short circuit level. It gives an indication of the voltage dip experienced near the generation in the event of a feeder outage. The connection of induction generators to high impedance circuits may lead to voltage instability problems if the SCR is not kept within acceptable limits [5]. The dip in wind farm terminal voltage that results from a fault can result in an acceleration of the induction generator, leading to overspeed. If the speed is increased to a level above the critical value, the generator will accelerate out of control. This will lead to voltage collapse as the induction generator absorbs more reactive power [6]. If the short circuit level is large enough, the transient voltage dip will be limited and the system will remain stable. The contribution of other generators to the SCL is considered, as it may be significant depending on the proximity of the bus. The phase angle at the busbar is omitted as an extra margin of safety. It could be included and the allowable ratio set to a lower value such as 6%. A value of 10% is largely in line with values used by other utilities and is in line with the value recommended in the European standard EN50160 [7].

Voltage Rise Effect

The rise in voltage occurs if there is low demand, which leads to a large amount of power flow along lightly loaded lines with high impedance. The resistive element of the lines on distribution networks is higher than other lines. This leads to an X/R ratio of approximately 1 rather than a more typical value of 5, as on transmission networks. The voltage must be kept within standard limits at each bus. This analysis is carried out under minimum load conditions as this is the worst case scenario for voltage rise. Both the standby and normal forward feed conditions are considered. There is usually more than one possible standby feeding arrangement, but the most severe feeding condition is usually readily identifiable.

IRELAND'S NETWORK STRUCTURE & PARAMETERS

The Irish transmission system is made up of over 5,800km of lines at voltages of 400kV, 220kV and 110kV. The 159,000km of distribution network includes the national 38kV sub-transmission network and the 110kV sub-transmission network in Dublin, a medium voltage (MV) 20kV and 10kV network along with low voltage networks.

In Ireland EG is typically connected at 38kV or MV. It is a mixture of renewable and conventional energy sources - wind, small scale hydro, combined heat and power (CHP), photovoltaic and landfill gas. The vast majority of applications for connections coming into the DNO are wind farm projects. These wind farms are typically located in remote areas where there is very little existing network and also very little demand for electricity. As of January 2004 there was approximately 500MW of generation either connected to the Irish distribution network or with signed connection agreements, of which approximately 70% is wind [8]. The overall contribution from renewable energy has increased by 400% in the last 5 years. This upsurge has been driven by a concern for global climate change, the restructuring of the electricity market, interest from farmers in alternative sources of income and an increased demand for electricity [9].

There are no strict rules for deciding which voltage level to connect at, nonetheless it should be noted that in general the higher the voltage the higher the connection charge. Within each voltage level there are a number of options for connecting generation into the system. These are:

- Direct feed to 110kV/38kV or 110kV/MV station
- Direct feed to 38kV/MV station
- Tee connection onto existing line

If the capacity of a project is less than 5MW, connection to the MV network may be possible and is typically cheaper. Tee connections are not generally permitted on the 38kV network as they can lead to a decrease in the security of the system.

The structure of the network modelled is radial with normally open points separating sections of the network. Most EG in Ireland is located in rural areas. In Ireland the maximum number of buses that are fed along one line from the 110kV station (i.e. interdependent) is typically four or five. In such cases, while the sections are analysed separately they all have the common constraints of the transformer capacity

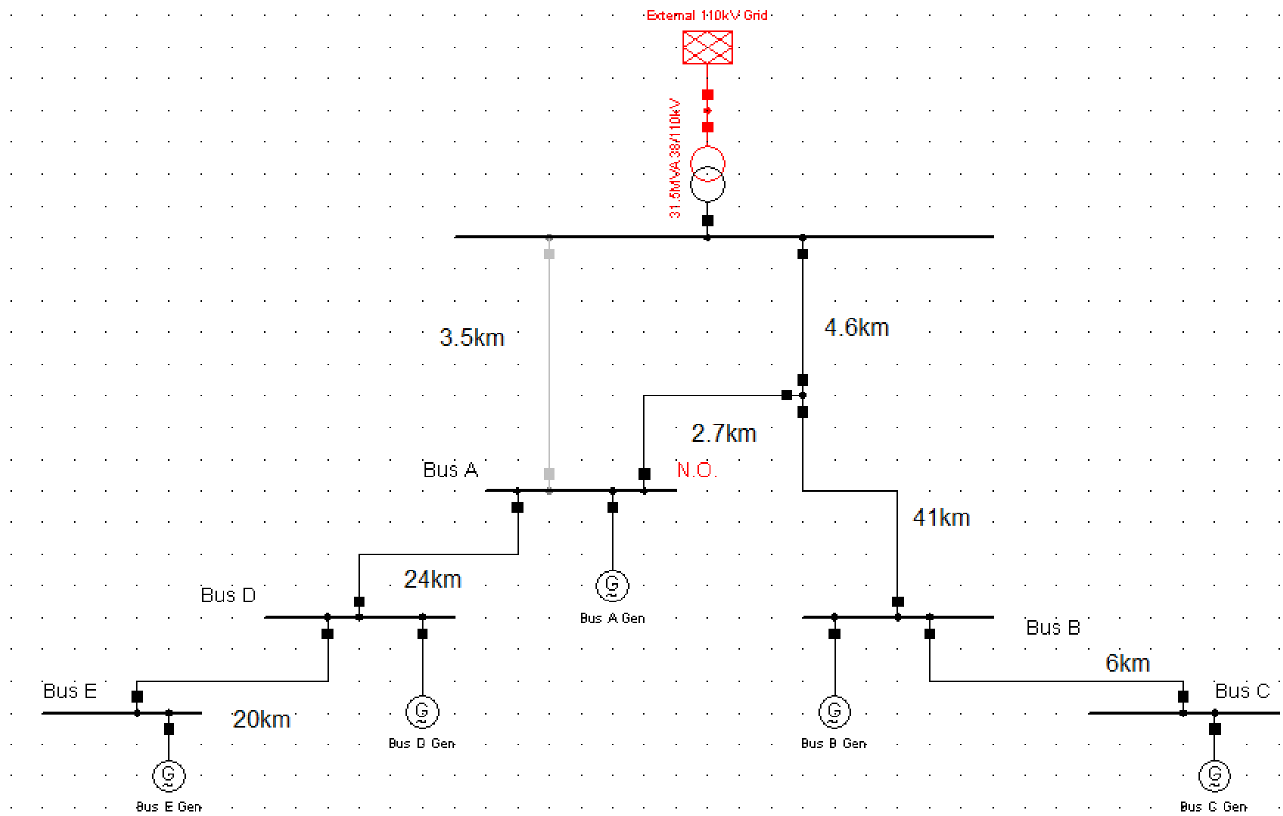

Figure 1. Single Line Diagram of 5-bus network in example 1

at the 110kV station and short circuit level. All generators are assumed to be fixed speed induction generators. They are connected in parallel at each bus with a power factor correction capacitor bank to maintain the power factor at 0.95 as required by the DNO. All necessary network data was obtained from ESB Networks, who are the DNO in Ireland [10].

RESULTS

The methodology was tested on a number of sample sections from the Irish distribution network. Results are shown here for a 110/38kV station with 5 buses and a 110/38kV station feeding 8 buses. This section of network in example 1 is characterised by long lines feeding remote areas, resulting in voltage rise being a significant problem. The section in example 2 differs from example 1 in that there are more lines connecting the buses to the transmission system, resulting in less interdependence between the buses. Example 2 is located in a less rural area with higher short circuit levels.

Example 1

If 7MW are allocated initially to Bus E, only a further 4 MW may be connected at the other buses, resulting in a total EG capacity of 11MW. If the optimal allocation methodology is employed the total allocation is 22MW as shown in Table 1. The network sterilisation is avoided and the EG capacity is maximised, with approximately a 100% increase over the other case.

The voltage at Bus E is the most sensitive to power injections and also the voltage level at Bus D is highly dependent on the power injections at Bus E. This results in the voltage constraint being met at bus E and only another 4MWs permitted at buses B and C, being the least dependent on Bus E. When the optimal methodology is used, the dependence and interdependence of all of the buses on all of the constraints is taken into account, resulting in best use of the existing distribution network. Table 1 gives a summary of the results, illustrating the extreme case of network sterilisation versus the optimal allocation.

TABLE 1 – Generation Allocation

Bus	Sterilisation Case (MW)	Optimal Allocation (MW)
A	0	4.1
B	2	4.2
C	2	6
D	0	5.3
E	7	3.1
Total	11	22.7

Example 2

The second section of network that the methodology is tested on is an 8-bus section of distribution network as shown in Figure 2.

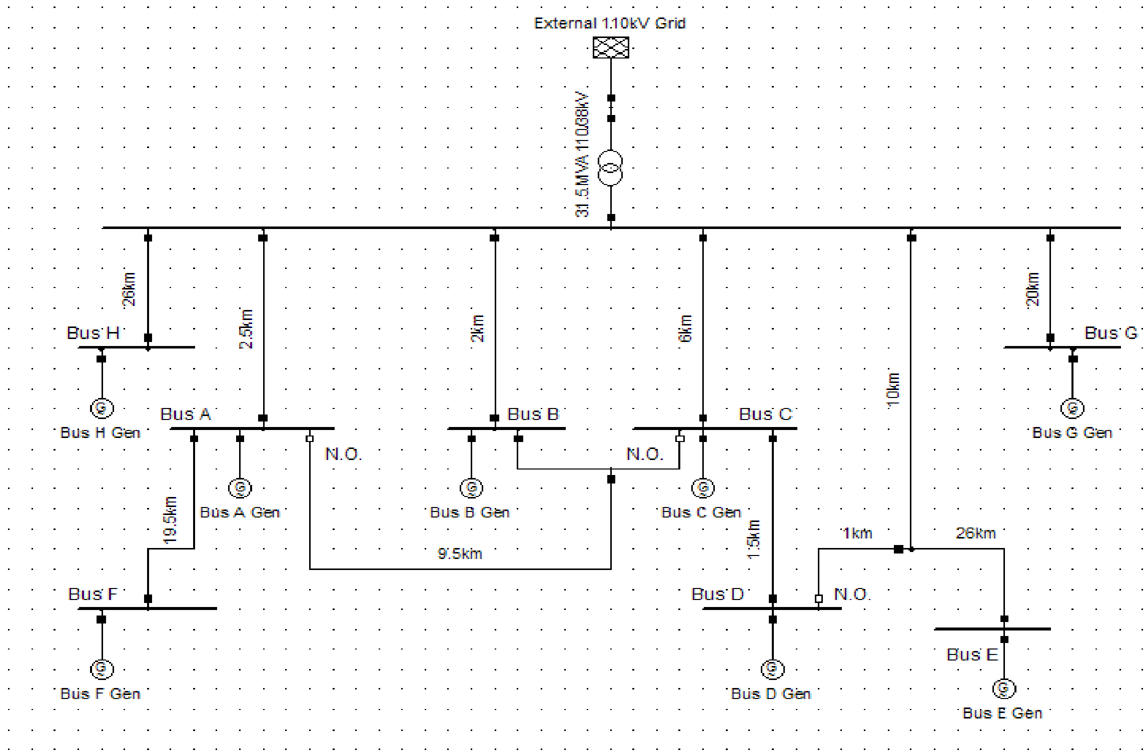

Figure 2. Single Line Diagram of 8-bus network in example 2

TABLE 2 – Generation Allocation

Bus	Sterilisation Case (MW)	Optimal Allocation
A	6	3.2
B	6	0
C	6	0
D	0	1.8
E	0	3.9
F	0	7.2
G	4	8
H	3	6.5
Total	25	30.6

As before, the results in Table 2 show the extreme case of network sterilisation and the optimal allocation as determined by the methodology. In this example the short circuit constraint is the only limiting constraint. Network sterilisation occurs in this case due to excessive generation connecting at the buses closest to the transmission station and hence contributing more to the short circuit level at that station. The optimal allocation methodology places most of the generation at the buses farther away from the transmission station. In this case the voltage constraint is not a limiting constraint. This is due to the amount of lines connecting the buses to the transmission station. This results in reduced interdependence of voltage levels between the buses. It can be seen from Table 2 that 5.6MWs of network sterilisation is avoided if the methodology is applied.

DISCUSSION

Two examples have been shown demonstrating the effectiveness of the optimal allocation methodology and the problem of network sterilisation. While the comparison has been made with extreme scenarios in examples 1 & 2, these scenarios are as likely as any other when EG applications are dealt with on a first come first serve basis. Network sterilisation is more severe, when the bus voltage levels are highly interdependent as in example 1. The methodology is most effective in rural areas with a high interdependence between the buses. Wind energy is currently the most prevalent form of EG in Ireland and other European countries and most of the energy resource is Ireland and the UK is in such rural areas. A significant penetration of EG, which in Ireland is almost exclusively from renewable energy sources can be achieved with no investment in the distribution network other than the cost of installing the generator. However the methodology developed here is not restricted to just wind energy and can be applied to all forms of EG as new technologies emerge and become economically viable.

Over a ten to fifteen year period, which is the typical lifetime of a wind farm project, some of the network conditions will change, possibly causing constraint breaches. Firstly it is assumed that the load will grow. This load growth will only serve to lessen the voltage rise effect. It will increase flows along the lines and therefore losses. In addition the SCLs will possibly increase, which may cause problems with equipment ratings. The transmission system operator's forecast statement contains predicted SCLs for the next seven years. This enables an accurate determination of future network conditions.

Existing distribution networks are passive, in that they were designed and built purely for the delivery of electricity to the customer. The introduction of EG is changing the characteristics of the distribution network. It has led to increased and bi-directional active and reactive power flows, along with wider variation in voltage levels, both of which affect the operation of equipment on the network and the level of losses. As such EG can defer planned network reinforcement, but may also require network reinforcement of both the distribution and transmission network. Several solutions have been proposed to overcome the constraints associated with EG [11]. In some cases a single constraint, which only occurs very infrequently may place a barrier to a significant further penetration of EG on a network section. In such cases a solution could be implemented, which will permit a significant increase in EG capacity for a relatively small investment. The solution may be in the form of non-firm access, which entails the generator constraining off, when an infrequent constraint is breached.

CONCLUSION

Results have been presented highlighting the problem of network sterilisation and demonstrating the effectiveness of the optimal allocation methodology for EG on different parts of the Irish distribution network. By application of the methodology the EG capacity of the existing distribution network is maximised. Once the utilisation of the existing network has been maximised, investment will be required to achieve a further penetration of EG.

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