The Probabilistic Integration of Demand-Side Load and Generation in a Representative Irish Distribution Network

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***Abstract*-This paper introduces a methodology for investigating the behaviour of a distribution network incorporating both load variations and variable micro-wind generation output. The probabilistic methodology is applied to a representative model of the Irish Distribution Network. Application of a selection of commercially available micro-wind turbines to the model is investigated for a range of load and generation scenarios based on a standard load profile and varying mean wind speed. Analysis of the results of the analysis forms the basis for defining the limitations of the methodology but also presents the opportunities for future work.**

I. INTRODUCTION

This paper advances the work in [1], where a model was developed to analyse the impact on a distribution network, in the terms of voltage rise of increasing penetration of micro generation and more specifically, micro-wind generation. Indeed, [1] was itself based on the systems described in [2] and [3]. In a report commissioned by *Sustainable Energy Ireland* (SEI) investigating the costs and benefits of embedded generation in Ireland [3], analysis for the context of micro-generation stated that voltage rise problems would not be encountered for the worst case scenario (each consumer having 1.1kV of generation whilst at minimum load of 0.16kVA).

This model is compiled employing MATLAB© to implement a *Distflow* routine as outlined in [4]. The Distflow approach derives the bus voltage of a weakly meshed network by iteratively evaluating the Load Flow solution of the modeled network under varying load/generation scenarios.

The Representative Irish Network which is considered in this analysis is shown in Figure 1. The system comprised of:

- One 500MVA Source
- Two 10 MVA Transformers (YY0, 38/10.5kV), auto-tapping to -20/+10% in steps of 1.67% and an AVC scheme with bandwidth of 2.5%
- Five, 10kV Distribution feeders with one modeled in detail
    - o This feeder is 3km long with 1.5km being 185mm^2 10kV PICAS and the remaining 1.5km being of 95 mm^2, 10kV PICAS
  - The detailed feeder contains ten 10/0.433kV Substations (fixed tap transformer), each substation having four LV feeders.
  - One of the LV Feeders is modeled in detail
    - o This feeder is 300m long with 150m being 185mm^2 415V CNE and the remaining 150 being of 95mm2, CNE.

The model developed in [1] was compiled for a range of scenarios:

- Maximum Demand on each substation (of each 10kV feeder), 0% Generation
- Minimum Demand on each substation (of each 10kV feeder), 0% Generation
- Minimum Demand on each substation (of each 10kV feeder), 100% Generation

Each substation, serves 312 customers (over three phases) and each customer is modeled as having an *After Diversity Maximum Demand* (ADMD) of 1.28kVA and the potential of affording a micro-generation technology with capacity of 1.1kVA. Each substation was modeled with a load factor of 50%.

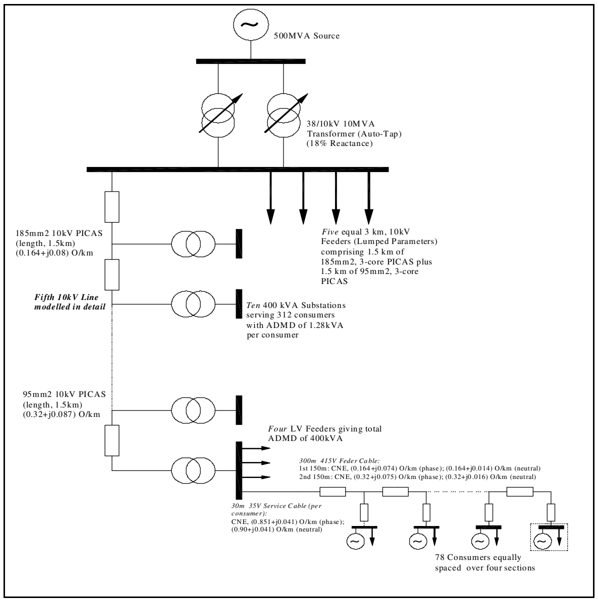

Figure 1: 38/10/0.4 kV Distribution Network Model

These scenarios represent the extremes of possibility. This paper further develops this model by integrating variable load and generation. This is implemented by using a probabilistic approach to the modeling of the wind speed of the micro-wind turbines. This variable micro-wind generation is combined with load profile data as provided in [6] which represents standard domestic load profiles developed for the Irish Electricity Market. These were utilized to determine the variation in voltage profile for the LV network as a result of both load and micro-wind generation. Similar work has been undertaken for a *Small Scale Energy Zone* (representing a total of 96 LV consumers) in [5] where a dynamic model which integrated variable wind speed in terms of a minimum load of 0.16kVA and a percentage of customers having a 1.1kW generator connected, produced results suggesting that voltage tolerance is breached at 114% penetration level.

The approach taken here is to apply a single (but variable) wind speed to all connected generation. This is considered acceptable as it is assumed that there would be little variation of wind in the area (excluding the effects of obstruction or shading) encompassed by the representative Distribution Network. Independently varying 'bulk' connected load of the connected consumers at the sectionalized connections of the LV feeder was also considered acceptable as a compromise to individual manipulation of each consumer's load.

Analysis of voltage profile over the course of representative days in different seasons was implemented for a sample of commercially available micro-wind generator units relative to the load profile.

Distflow is employed as the optimal methodology to derive the load flow results for the network as standard load flow approaches (Newton Raphson, Gauss Seidel etc.), have difficulties in converging due to the high X/R ratios characteristic of distribution networks.

II. THE METHODOLOGY

Figure 2 illustrates a flow chart describing the methodology utilized in deriving the bus voltages for the network model

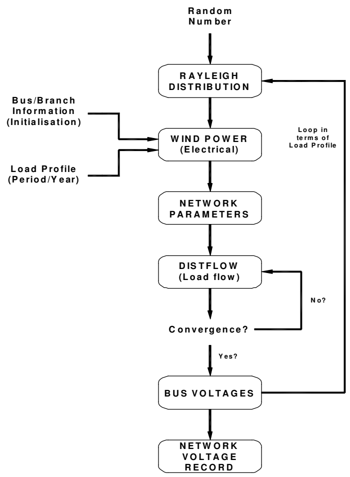

Figure 2: Flow Chart illustrating the methodology in deriving a load flow solution for variable load/gen

The approach is summarized as follows:

- A random number is generated in MATLAB and through (1) a Rayleigh probability distribution is created to represent a varying wind speed.

$$V(i) = V_{Mean} \times \sqrt{\frac{-4}{\pi} \times \log(1-F)} \tag{1}$$

where:

$V_{(i)}$ is speed derived for each iteration of the program and N is the total number of time periods considered. The analysis is carried out with a 15 minute interval to align with the load model data. F is a uniformly distributed random number. The other assumptions made in relation to the analysis are as follows:

- Uniform penetration of a chosen wind turbine across the network
    - Generation is 'lumped' to the respective buses, but contrary to [1], this lumped generation is variable with respect to the applied simulated wind speed.
- The chosen wind turbine is modeled in terms of
    - Cut-in/out speeds
    - Rated Power (at rated wind speed)
    - Actual power output is based on the derived Rayleigh distribution in conjunction with the specific mean speed
- The load data acquired was for a representative year based on 15 minute intervals [6].
    - Figure (2) illustrates the load variation over the year.
- Automatic tapping of the 10 MVA Transformers is not implemented.

Figure 2 shows the load variation over the course of one year, with a peak demand of 1.73kW and an annual consumption of 6000kWh.

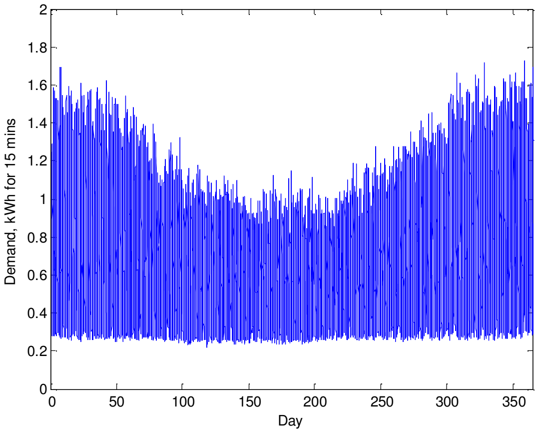

Figure 3: Load Profile Representation of Irish Domestic Dwelling

III. ANALYSIS

Three different types of commercially available wind turbines (Table 1) were modeled for the following scenarios:

- Load/Gen at unity power factor (p.f.)
- Load @ 0.95 p.f.; Gen @ unity
- Load@ unity; Gen @ 0.95 p.f.

  - Load/Gen @ 0.95 p.f.
- Two periods over the representative *year* were considered in detail:
  - The 5th of January and 5th of July, with mean wind speeds of 5.49m.s^{-1} and 3.65m.s^{-1} respectively [7]
  - The analysis is performed in terms of the bus at the end of one of the LV feeders

TABLE I
SAMPLE OF COMMERCIALLY AVAILABLE WIND TURBINES

Model	Reference	Cut-in Speed	Cut-out Speed	Rated Speed	Rated Power
Whisper 200	Gen 2	3.58 ms^{-1}	>50 ms^{-1}	14 ms^{-1}	1.5 kW
Proven 2.5	Gen 3	2.5 ms^{-1}	>50 ms^{-1}	12 ms^{-1}	2.5 kW
Swift	Gen 4	3.58 ms^{-1}	>50 ms^{-1}	14 ms^{-1}	1.5 kW

IV. SIMULATION RESULTS

The simulations performed, as summarised in Table 2, were in the context of voltage profile across the entire network, but for simplicity, the voltage at the remotest bus on an arbitrary LV branch (400V) was recorded. The voltage magnitude for this bus is measured against the tolerance of +10/-6% of nominal voltage for the Distribution Network. The 5th of January and 5th of July were specifically chosen on the basis that there would be considerable differences to load and generation profiles due to both the associated mean wind speed as well as load profile.

TABLE 2
VARYIABLE LOAD AND GENERATION SIMULTION SUMMARY

	5th January & 5th July	
	Load	Generation
100% Generation Connection	Unity	Unity
	0.95	Unity
	Unity	0.95
50% Generation Connection	Unity	Unity
	0.95	Unity
	Unity	0.95

The results of the simulations are illustrated in the following graphs. Figure 4 illustrates the relationship between the simulated wind speed and the generation of 5th January with 100% generation at unity pf. The typical daily load demand as obtained from [6] is also shown. The different levels of output from the modeled generators are clearly discernable with the Proven 2.5 having the biggest contribution. As the rated outputs of the Whisper and Swift Models are closely aligned 1kW and 1.5kW respectively, the generated outputs from both models are very similar at given the wind speed profile. Fig. 5 shows the voltage over the course of the day which tracks the simulated wind speed.

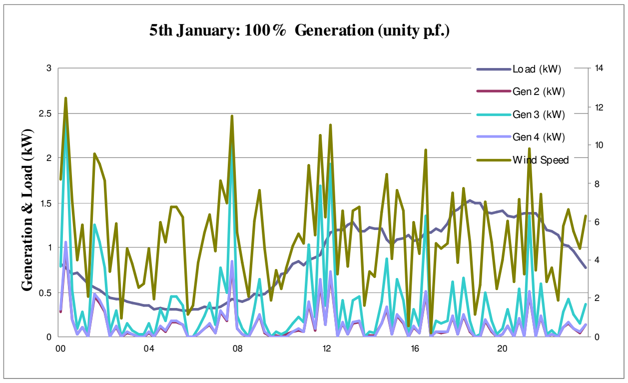

Figure 4: The relationship between generation and wind speed reflected in terms of the Demand profile

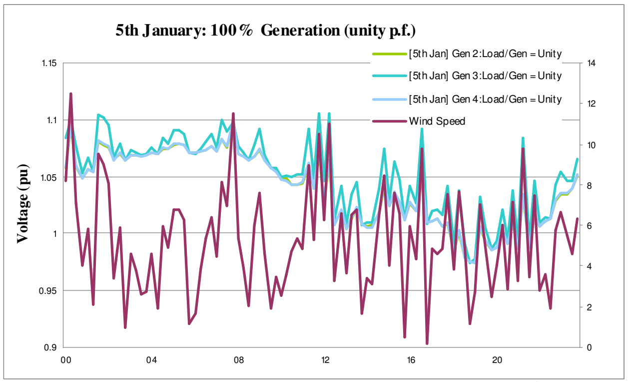

Figure 5: Voltage variation with respect to wind speed for the 5th January

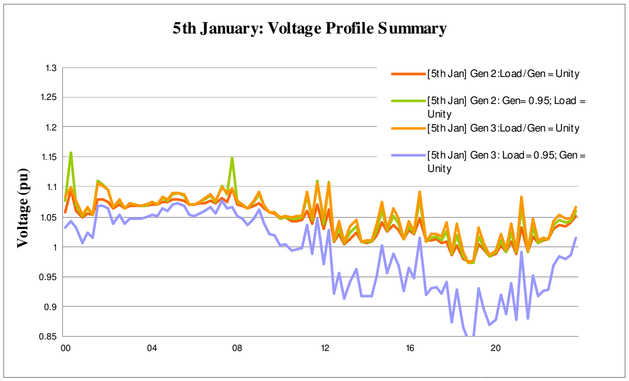

Figure 6: Voltage Profile for all cases during the 5th January

Fig. 6 illustrates the voltage profile for the 5th of January. The same analysis was performed for the 5th of July producing similar results albeit with a lower voltage magnitude due to the lower generation for the date. There are increased levels of generation on the 5th of January due to the increased mean wind speed being employed and as a result, there is a higher voltage level experienced by the bus under scrutiny for the demand applied.

Figures 7 and 8 depict the voltage spread for the varying load/demand ratios for the respective dates under scrutiny. The minimal impact afforded by the generation due to the lower mean wind speed is particularly evident in Figure 8.

Also, the lower consumer demand is also evident in that the breaches of the lower voltage threshold are less frequent and their level diminished.

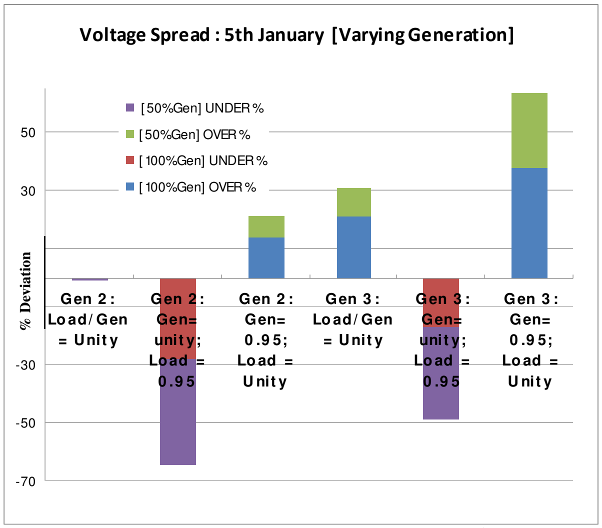

Figure 7: Voltage Spread for all contexts during the 5th January

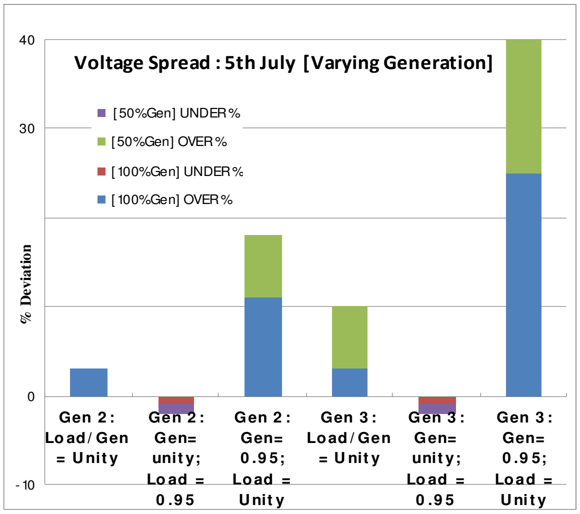

Figure 8: Voltage Proliferation for all contexts during the 5th July

Figure 9 shows the impact on the voltage level with respect to the range of generators. This is placed against the background depicting a probability density function describing the wind speed for the year with mean 6ms^{-1}. Clearly, the Proven 2.5 with its greater output contributes most frequently to breaching the upper voltage limit of 1.1pu. The graph also illustrates that for each of the wind turbines, the most frequent voltage is 1.08pu, which could be considered excessive and this is irrespective of the wind turbine chosen. The mean wind speed of 6 ms-1 was chosen as a more realistic year-round average.

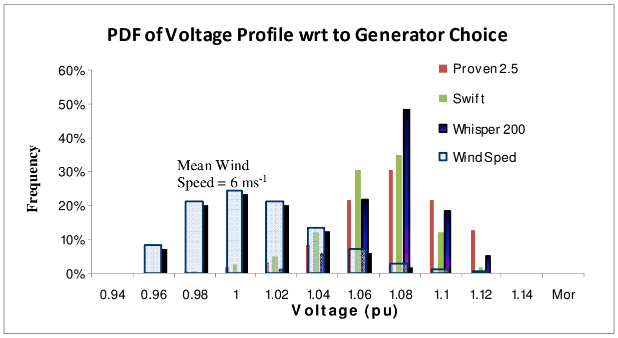

Figure 9: PDF of Voltage Proliferation in terms of the different Generators

CONCLUSION

The work presented introduces a methodology that can investigate distribution network behavior when incorporating both load and generation variation. A sample of commercially available micro-wind turbines were utilized in a representative distribution network model with their outputs based on their characteristics and wind speed derived from a specified probability distribution. This model was subjected to mixed generation and loading conditions and demand was based on a standard load profile for domestic consumers. Voltage variation was monitored. Voltage is dependent on both load as well as generation, with voltage rise resulting from reverse power flows from the connected generation.

Generation based on wind will result in fluctuations mathching the turbulent nature of the wind speed. The model had no voltage control on the variable tap distribution transformers and the simulations illustrated this by virtue of both the frequency of voltage tolerance breach and the spread of voltage for the different load/gen scenarios.

Indeed, voltage control by virtue of transformer tapping presents a considerable challenge for demand side management due to the stochastic and variable nature of wind.

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[7] MET Eireann, 30 Year Climatic Averages, http://www.met.ie/climate/dublinairport.asp