COMPARISON OF ANALYSIS METHODS FOR GENERATOR CONNECTIONS

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ABSTRACT

This paper presents a network operator perspective on the methods used for analysis of new generator connections to distribution networks in Great Britain. The applicable standards are summarized and the analysis methods normally employed by developers, or their consultants, are described. Different methods can produce different outcomes and some examples of this are presented. The network operator has a role to play in reviewing the analysis results but the customer remains responsible for their impact on the network.

INTRODUCTION

In preparing to connect a new generator to a distribution network in Great Britain (GB) the developer must perform various types of analysis to inform the design and demonstrate that the generator will comply with all applicable standards. Results from this analysis are shared with the relevant distribution network operator (DNO) for review and comment. Different developers and consultants can use different analysis methods, even when they are seeking to demonstrate compliance with the same standard. The DNO has a role to play in reviewing the analysis results and providing advice, which can be challenging when the methods used vary widely. Taking account of the analysis and other factors, the DNO will reach a decision on whether new generators can be energised but the customer remains responsible for their impact on the network throughout the lifetime of the generator. Thus, it is in everyone’s interest for pre-connection analysis methods to be robust and consistent.

STANDARDS

New generators connecting to GB distribution networks must comply with a range of standards and regulations. Primary legislation includes:

- Electricity Act 1989 – Sets out the regulatory framework and licensing regime for the UK Electricity Supply Industry.
- Electricity at Work Regulations 1989 – Imposes duties to limit the risks involved in using electricity at work.
- Electricity Safety, Quality and Continuity Regulation 2002 – Secures the safety of the public and ensures a proper and efficient supply of electrical energy.

Generators connecting to the Transmission Network or with bilateral contracts with National Grid must comply with the GB Grid Code [1], which covers all technical aspects relating to the planning, operation and use of the interconnected transmission system and the operation of electrical apparatus connected to the system. Small generators connecting to a distribution network must comply with the Distribution Code (DCode) [2]. If a generator is large enough to have a contract with National Grid but connects at distribution level then the DNO may insist that it complies with both the Grid Code and DCode.

The codes refer to a number of other Engineering Recommendations. Those most relevant to generator connections are:

- G59 – Recommendations for the connection of private Generating plant to the Electricity Boards Distribution System [3]
- G83 – Recommendations for the Connection of Type Tested Small-Scale Embedded Generation (Up to 16A per Phase) in Parallel with Low Voltage Distribution System [4]
- G5/4 – Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission and distribution systems in the United Kingdom [5]
- P28 – Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom [6]
- P29 – Planning limits for voltage unbalance in the United Kingdom for 132kV and below [7]

This paper focuses on the analysis performed to demonstrate compliance with G5/4 and P28 because these are often the most challenging for new generator connections. Harmonic distortion is a growing problem because of changes in the types of generation and demand being connected and the greater use of underground cables. Voltage fluctuations, especially those due to transformer energisation, are often a problem because of the trend to connect larger generators at lower voltages.

It is important to note that both of these standards are currently under review. P28 is currently undergoing a comprehensive review, partly to address changes in the network due to the proliferation of distributed generation [8]. It is also proposed that this update will address the new technologies being connected such as electric vehicles, energy storage and heat pumps. There have also been changes to the types of lighting installed, which can be more or less sensitive to voltage flicker and are one of the main methods by which the public will notice voltage distortion in their supply. Among the changes expected to be introduced with G5/5 is a different approach to the allocation of available headroom to new connections.
PRE-CONNECTION ANALYSIS

To support the design of the connection and ultimately to demonstrate compliance with the standards, the developer will typically engage a power systems consultant to perform a range of studies. The analysis will normally cover load flow and short circuit studies to demonstrate voltage regulation and help in specifying cables, transformers, switchgear and other equipment. The analysis will also explore power quality issues like voltage flicker, harmonics and the voltage dips that occur on transformer energisation, and thereby seek to demonstrate compliance with G5/4 and P28.

The requirements have remained the same for several years and are generally well understood. Although the continuing growth in small-scale generation means there are many new entrants to the market and it is sometimes necessary for the DNO to explain the requirements to new customers unfamiliar with the industry and the established processes.

The limits specified as part of the DCode (DPC 4.2.3.3) state that the limits for transformer energisation for normal routine switching operations should not cause a voltage fluctuation outside the limit of +/-3% as set out in P28. For events that are infrequent, happening no more than once per year, there is an allowance to go up to +/-10% with the caveat that a worst case energisation could cause a larger voltage step. Should this occur more than once per year, the DCode says the 3% limit shall be applied.

P28 is mainly concerned with motor starting but the same limits have been adopted for the transformer energisation on new generator connections. It sets a limit of 3% for normal switching operations, but also makes reference to a limit of 6% for infrequent events (P28 Addendum 1, Part 3). It is clear that what is of interest is the RMS voltage change at the point of connection (POC) 30 ms after closing the circuit breaker.

It is important for the pre-connection analysis to be done properly, using the best available data and robust methods. It is not simply a “box ticking exercise” as it is quite possible for new generators to have an adverse and unacceptable impact on the network and other customers. Recent experience at SPEN includes cases where harmonic distortion and voltage flicker have been higher than anticipated.

COMPARISON OF METHODS

Based on the authors’ experience, the issues that most often give cause for concern are harmonics and transformer energisation. Problems are more likely when generators seek to connect at voltage levels lower than might previously have been done or in locations that are deeply embedded in distribution networks. The lower fault level, or more importantly the higher the ratio between generator size and fault level, makes it more likely that problems will arise.

Connecting at a lower voltage level is generally cheaper, in terms of the equipment involved and also normally in terms of the distance to a point of connection on the existing network. In the past, generators in the 10 MW range would normally connect at 33 kV but applications are now regularly received to connect generators in this range at 11 kV. This covers a wide range of technologies, from sites with a few wind turbines to inverter-connected battery storage.

Harmonics

Engineering Recommendation G5/4 specifies three stages of analysis; the smallest generators need comply only with Stage 1. For generators connecting below 33 kV, the reports submitted to DNOs normally aim to demonstrate compliance with Stage 2. If the existing background levels of distortion are below 75% of the limits, this is based on assessing only the injected harmonic currents. If background distortion is high, the Stage 2 limits are exceeded, or for all connections at 33 kV or above, it is necessary to perform the more complicated analysis of Stage 3, which assesses the impact on harmonic voltage distortion on the network. This requires obtaining data from the DNO on the network impedances.

Most analysis focuses on distortion due to harmonic currents injected by the generator. As more connections are made using underground cables there is a growing risk of problems due to resonance conditions on the network. The combination of inductance in transformers and capacitance in cables may result in a series resonance that has the effect of amplifying background harmonics. Although not directly associated with the harmonic currents being injected by a generator, this sort of problem is still attributable to the new customer. The problem may not become evident until commissioning, by which point the options for mitigation have been reduced and the costs have increased. This is an area that deserves further attention in pre-connection analysis.

Transformer Energisation

Engineering Recommendation P28 specifies limits on voltage fluctuation and flicker. Pre-connection studies are performed to demonstrate compliance. In the authors’ experience, voltage step change and flicker limits are normally satisfied but transformer energisation is most likely to present problems. This is also the area that sees the greatest diversity in analysis methods and assumptions. This is because there is some ambiguity over the requirements, different methods can be applied and still produce valid results, and those performing the analysis may choose the method to suit the circumstances, i.e. where one method indicates limits are exceeded, another method might be used or assumption changed to produce more favourable results. The DNO is then asked to interpret the results and advise accordingly.

As with other types of power systems analysis, there are three main approaches to estimating the voltage dip likely to occur on transformer energisation:

1. Steady state calculation, possibly in load flow but in this case more likely to be a direct calculation using a particular formula.
2. Balanced RMS/phaser dynamic simulation, as is
more commonly used for stability studies. This type of analysis is rarely used for transformer energisation although it is often used to study motor starting.

3. Three-phase electromagnetic transient (EMT) simulation, which typically has a time step of 0.1 ms or less and produces full waveform plots.

Within each of these methods there can be different assumptions and choices made by the analyst. One that applies to all methods is the treatment of the DNO network and what it means for fault level at the Point of Connection (POC). Some studies assume minimum fault level, which may arise after a credible outage and with other generators out of service. Some reports argue that outages due to faults and maintenance should be disregarded because they will persist only for short periods. The most comprehensive analyses consider both minimum and maximum (normal) fault level and present results for both. Often the voltage dips will be within limits for maximum fault level but exceed limits for minimum fault level. The DNO is then invited to make a judgement on acceptability.

Consultants’ reports will also make different arguments about the applicable limit. Sometimes the 3% limit in P28 is treated as a hard limit while other reports claim that transformer energisation is “infrequent” and refer to the 6% limit, or the 10% limit given in the DCode. This is an area that requires clarifying, which is one reason why P28 is currently under review.

The quickest way to estimate the effect of transformer energisation is to use a simple formula. The inrush current of a transformer is often given as multiple of rated current, typically between 5 and 10 times. However, this refers to the peak inrush current, which has a significant DC offset and high harmonic content. The most pessimistic and straightforward analysis is to compare the “inrush MVA” of the transformer with the fault level, or short-circuit capacity, at the POC. Generators are often quite deeply embedded in distribution networks and connections are often sought in locations with a fault level at 11 kV of around 100 MVA. A typical modern wind turbine might have a transformer rated 2.5 MVA. If the inrush current of the transformer is stated as being 8 times rated current then the voltage dip might be estimated to be:

$$V_{dip} = \left(\frac{8 \times 2.5 \text{ MVA}}{100 \text{ MVA}}\right) \times 100\% = 20\%$$

Another method uses a formula to adjust the effective inrush current:

$$I = \frac{I_o}{(1 + I_o \times X)} \text{ (per unit)}$$

where Io is the transformer inrush in per unit of rated current and X is the effective supply reactance in per unit on the transformer base. In our simple example,

$$X = \frac{2.5 \text{ MVA}}{100 \text{ MVA}} = 0.025 \text{ per unit}$$

And the inrush current is adjusted to,

$$I = \frac{8}{(1 + 8 \times 0.025)} = 6.67 \text{ per unit}$$

Utilising the adjusted inrush current value in the previous equation alongside the assumption that only 30% of the inrush current is comprised of the 50 Hz component gives:

$$V_{dip} = \frac{(6.67 \times 30\% \times 2.5 \text{ MVA})}{100 \text{ MVA}}$$

$$V_{dip} = 5\%$$

If a full EMT analysis is performed then the report will normally explain the various assumptions that have been made on issues like saturation characteristics, residual flux and sympathetic inrush. P28 does not give any advice on the treatment of these issues and it relies on the consultants applying sensible engineering judgement. The instantaneous values in the waveforms produced by the EMT analysis are converted to RMS values; this is normally done in the simulation software. This approach includes the effect of all harmonic components on the overall RMS voltage, which is preferable to the simple assumption on the percentage component at 50 Hz.

In EMT analysis the key factor used to assess the relative risk of different voltage dips is switching angle. Unless a circuit breaker is fitted with point-on-wave switching, this is a random variable that can be considered to be uniformly distributed. The analysis may simply assume the worst-case switching angle, or a number of simulations may be run to test the effect of different switching angles. The results are often presented as a chart with switching time or angle on the x-axis and the voltage dip results plotted against the 3% limit. Typically, if the distribution of results is such that more than 50% are below the limit then this will be presented as being compliant.

Where a site has more than one transformer, the analysis will normally consider the energisation of single and multiple transformers, and normally the energisation of the whole site. It is often the case that one transformer can be energised with a voltage dip below 3% but trying
to energise more than one exceeds the limits. The solution is to install sufficient switchgear to allow separate energisation of the transformers and then to specify a switching sequence pattern. This ensures that the times between switching events are large enough to meet the P28 requirements.

If the analysis indicates that limits will be exceeded for energising a single transformer then the solution normally involves the use of pre-insertion resistors or a pre-magnetisation arrangement that energises a smaller transformer first then energises the larger transformer from its LV side before connecting at HV.

Ultimately, the pre-connection analysis can only offer a prediction of what the voltage dips might be. The real-life behaviour once a generator connects will depend on the conditions at the time and on random factors like the point on wave of circuit breaker switching. An example of the voltage dips measured for the energisation of a wind farm site is shown in Figure 1 below. This shows the distribution of voltage dips seen at two nearby points on the 33 kV network for the initial energisation of 3.75 MVA transformers at a wind farm site. Prior analysis had identified the risk of voltage dips approaching or exceeding 3% and so the transformers were energised individually at approximately 10 minute intervals. The results show a successful outcome, demonstrating the risk of voltage dips exceeding the 3% limit while the majority of disturbances are small enough not to be of concern to other customers.

The DNO has a responsibility to all customers, present and future, and must ensure that new connections do not result in network behaviour outside of the standards. This is not merely a theoretical problem as real problems arise on the network on a regular basis.

The potential impact of excessive voltage dips caused by transformer energisation can range from light flicker to tripping of sensitive loads or stalling of motors. Excessive harmonic distortion can result in additional heating of transformers and neutral conductors, which could eventually lead to tripping, and potential interference with customer equipment.

Developers sometimes argue that assessment of harmonics or voltage fluctuations at their POC is too onerous and instead present results calculated at the point of common coupling (PCC). This is the point on the network upstream from the point of common to the connection of other customers. The customer may be willing to accept conditions at their POC that are outside of limits, and will point out that other customers will only “see” the conditions at the PCC. This argument is sometimes accepted, especially where the geographic conditions make it extremely unlikely that any other customers will ever connect at the same POC. However, the customer should be warned that the POC is part of the DNO network and other customers may connect there in future. If a new customer does come along in future then the incumbent generator may be required to solve whatever problems they are causing; this would be at the generator’s expense.

SPEN recently saw significant flicker problems at a primary substation where a wind farm had recently been connected. Investigation utilising power quality monitors confirmed the distortion coincided with periods of generation. The wind farm was disconnected. The customer, through the support provided by the turbine manufacturer, was able to solve the problem by making a change in inverter configuration settings and was allowed to reconnect. It is notable that the number of complaints was actually quite low, despite the severity of the distortion; this is believed to be due to the proliferation of LED lighting but will require further investigation.

The purpose of the pre-connection analysis is to anticipate any potential problems and mitigate accordingly. The role of the DNO is to support the customer, with data or advice as appropriate, to allow them to assess the risks. The DNO does not “approve” the analysis and then accept all risks associated with the connection. Even when the DNO allows the generator to be energised, it is at the customers own risk. The customer remains responsible for their impact on the network throughout the lifetime of the generator.

The DNOs, and the industry as a whole, must respond to the challenges posed by new technologies and market developments by reviewing the applicable standards and adapting processes as appropriate. This can be seen in the current reviews of G5/4 and P28. For example, it is expected that in P28 Issue 2 the 3% limit shall be extended to 6% for infrequent events. Alongside this will
be a comprehensive description of what is classified as “frequent” or “infrequent” occurrence with a clear distinction and values of allowable limits for normal operation, normal switching and emergency switching events.

CONCLUSIONS AND RECOMMENDATIONS

It is recognised that analysis of prospective generator connections must be managed in terms of time, resources and the availability of data, as well as reflecting the risks associated with inaccurate or inadequate studies. Based on our experience the analysis reports delivered by developers are typically of a high standard and provide the level of confidence necessary to allow generation connections to progress. It is hoped that by sharing a DNO perspective with the wider community this paper will help to further improve understanding and reduce the costs of analysis for customers.

REFERENCES


[7] P29 – Planning limits for voltage unbalance in the United Kingdom for 132kV and below