REAL TIME FAULT LEVEL MONITORING

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ABSTRACT

There is greater pressure than ever before for DNOs to offer customers a low cost and timely connection of Low Carbon Technologies to their networks. Wherever possible DNOs are turning to innovative solutions to free up network capacity to facilitate these connections. The development of Real Time Fault Level Monitoring equipment is seen as one way to free up capacity on networks constrained by fault level. Through the development and deployment of this innovative technology it is expected that DNOs will be able to actively manage the network fault level and the contribution from customers. SP Energy Networks in collaboration with Outram Research Ltd are leading the way with the development and trialling of this technology with initial results obtained from real world 11kV trials indicating that the technology is capable of generating accurate and reliable results.

THE FAULT LEVEL CHALLENGE

The management of fault level is one of the greatest challenges facing Distribution Network Operators (DNOs) worldwide. DNOs have obligations to provide timely low cost network connections whilst ensuring the design limits of plant and equipment are not exceeded. The challenge of meeting these obligations is particularly difficult when the requested connection would increase the network fault level above its acceptable limit. Any exceedance above equipment capability will result in increased health and safety and network security risks. Firstly, the integrity of plant and equipment encountering fault current higher than its rating cannot be guaranteed. Secondly, connections that require network reinforcement to overcome fault level issues are seldom timely or low cost. They often require investment in new plant or substantial network reconfiguration.

This challenge is further compounded by the drive to adopt Low Carbon Technology (LCT), particularly in the form of Distributed Generation. The associated connection requests often target congested commercial and industrial parts of the network. In fault level constrained areas these incremental additions to the network are frequently sufficient enough to cause fault level exceedance. The resulting connection offer will consequently include substantial network reinforcement costs or delays which are unacceptable to the customer.

SP Energy Networks Fault Level Issues

For SP Energy Networks (SPEN) this issue is prevalent and as a result fault level poses a major barrier to our transition from DNO to DSO as well as to reaching national carbon transition targets.

Figure 1 illustrates the scale of the issue, at 33kV, in one of the regions of our networks. Each node represents a 33kV substation. The majority of connections into this area of network would likely require fault level mitigation interventions. A similar image could be presented for various other regions throughout SPENs networks.

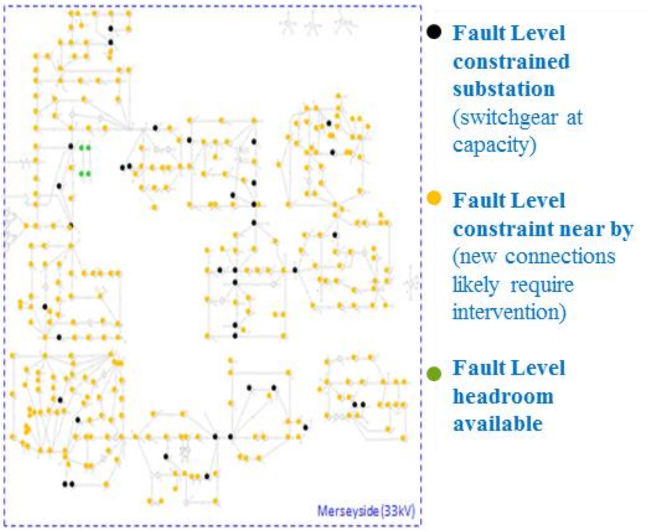

Figure 1 Merseyside 33kV Fault Level Constraints

Limitations of Present Fault Level Practices

The present industry practice for managing fault level is to calculate it using sophisticated modelling tools that consider the Network's construction, configuration, loading and the expected fault contribution from commercial and industrial customers. Whilst this approach is mature and has proven to provide an acceptable representation of the network, there are factors affecting fault level not readily available to the modellers:

- The accuracy of the DNO model is dependent on both measured and typical impedance parameters, also on information supplied by customers - particularly those relating to fault contribution.
- Distribution network fault levels are influenced by many factors, including: transmission network fault

levels; distribution network characteristics; operational running arrangements; customer's fault level in-feed. Not all of this information is readily available in real-time.

- As a result the models do not typically provide a real-time representation of the network fault level. Without this capability fault level cannot be actively and precisely managed to release non-firm capacity.

Any solution that provides high resolution real time network fault level information could be used to release fault level capacity, manage fault level constraints and facilitate a low carbon transition.

THE DEVELOPMENT OF FAULT LEVEL MONITORS

Natural Disturbance Fault Level Monitor

Back in 2010 SPEN and Outram Research Ltd (ORL) undertook an innovation project to develop a first of its kind Natural Disturbance Fault Level Monitor (PM7000FLM) [1]. The PM7000FLM was based on a power quality monitoring platform and was capable of measuring fault level on distribution networks. It did this through observing naturally occurring network disturbances such as load variations and the network's response to them. This yielded a measure of source impedance, and multiple measurements were aggregated together to mitigate noise and produce the fault level results. SPEN subsequently has had great success using the PM7000FLM at 132kV, 33kV and 11kV identifying the networks prospective fault level. The results obtained have either refined network models or have validated model results. In most cases the PM7000FLM has indicated that the actual fault level is lower than perceived by modelling alone.

Real Time Fault Level Monitor

Whilst the PM7000FLM complements existing practices by refining the accuracy of the network models, it does not provide the benefits of real time visibility / capacity release. Accordingly in 2016 SPEN and ORL embarked on a second collaborative innovation project to develop a Real Time Fault Level Monitor (RTFLM), building upon further learning from the Flexdgrid project [2].

TECHNICAL OVERVIEW OF THE RTFLM

The RTFLM exploits the same processing methodology as the PM7000FLM but with the addition of a built-in disturbance generator to apply its own artificial load to the network. This overcomes the dependence on naturally occurring disturbances which may or may not be present, and can reduce the time to produce a quality result from days/weeks to seconds. By measuring the current into a separate radial load, total fault level contributions from the network both upstream and downstream of the measurement point can be obtained.

Figure 2 shows the principal elements and network connection of the RTFLM generating 11kV results. Under processor control an inductive load is periodically applied to an LV bus coupled by a transformer to the target bus, typically 11kV or 33kV. Solid-state power switches are used to control pulse duration and frequency. The RTFLM takes direct inputs from the High Voltage (HV) busbar Voltage Transformers (VT) and Low Voltage (LV) Current Transformers (CTs) integrated into the RTFLM that measure the incoming load.

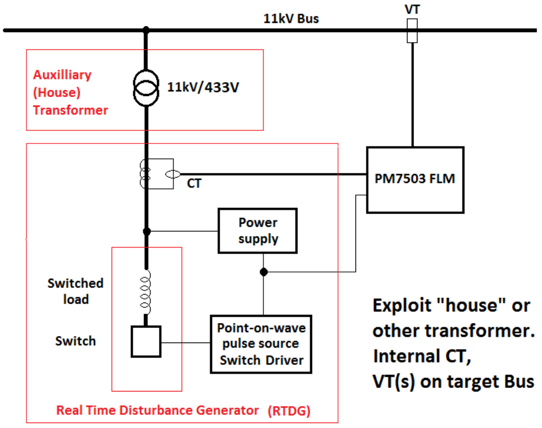

Figure 2 RTFLM Installation Single Line Diagram

The RTFLM has been designed with the aim of producing Peak Make and RMS break current prospective fault level measurements which may ultimately be used as real time updates to the network SCADA system. Frequent measurements and some form of averaging over 10 seconds was targeted to give largely independent 10 seconds SCADA samples for RMS fault level accurate to 1-2% rms. Depending on network noise, laboratory tests showed that this could be achieved with short 0.03 to 0.1% voltage disturbances at around 10 per second, with longer pulses a little less frequently.

This level of disturbance, small enough to be repeated without affecting power quality, could be created for a 1000MVA 33kV installation with a HV loading of ~10-30A rms. It is expected that general network noise will reduce at higher bus voltages, so although creating disturbances to work with is harder, it follows that proportionately greater disturbances will be required at lower voltages. The initial RTFLM installations at SPEN substations have been designed with both variable rates and sub-cycle pulse lengths.

Ten independent 20mH inductors provide the switched load. The ten inductors in this modular arrangement may be harnessed in parallel for 33kV operation, or a subset used for lower target voltages. If more were to be required (say at a noisy site or where results are required very quickly <1 seconds) the power switches, inductors and high current sections can be readily scaled.

The 10 x 20mH inductor set was chosen based on observed LV performance and signal / noise ratios. From hybrid simulations, using synthesised VT and CT signals fed into the RTFLM, it was expected that 4 inductors might be used for 11kV monitoring, and all 10 at 33kV. Final performance in a real substation would then depend on noise levels encountered, pulsing rates/lengths and acceptable averaging times. Switching the load of 2 – 20mH creates a disturbance on the target HV bus, (11kV in **Figure 2**). Pulse length affects peak current; a typical ½ cycle pulse produces between ~85 – 850A peak. This peak is diluted by the transformer coupling, so the current peak at HV and the resulting voltage disturbance are relatively very small – a few volts depending on the transformer characteristic and fault level.

The precise changes in current and voltage are measured by the RTFLM using the VTs and CT(s) and the complex impedance calculated. Voltage variation is measured directly on the target bus, current variation may be measured at LV or HV. If measured at LV as shown, transformer vector group, characteristics and loading all affect the LV current pulse transformation to HV and must be taken into account. If current is measured directly at HV, calculations are simpler.

Although the transformer may be large (and for LV current measurement must be taken into account). If a transformer already exists in a sub-station, either as an auxiliary or a distribution transformer, the logistics of RTFLM installation involve only connections at LV and may not involve any outage. VTs are usually already present on the target HV bus.

To avoid degrading voltage power quality and adversely affecting customers, the voltage variations are necessarily small or very infrequent. As a consequence, the signal / noise levels for voltage measurements are small; these are discussed later in this paper. The current measurements are larger and do not present the same challenge.

CHESTER 11KV TRIAL

The City of Chester in the North West of England is supplied via an 11kV interconnected meshed underground cable network between 5 substations each equipped with a 7.5MVA 33/11kV transformer. **Figure 3** shows a schematic overview of this network.

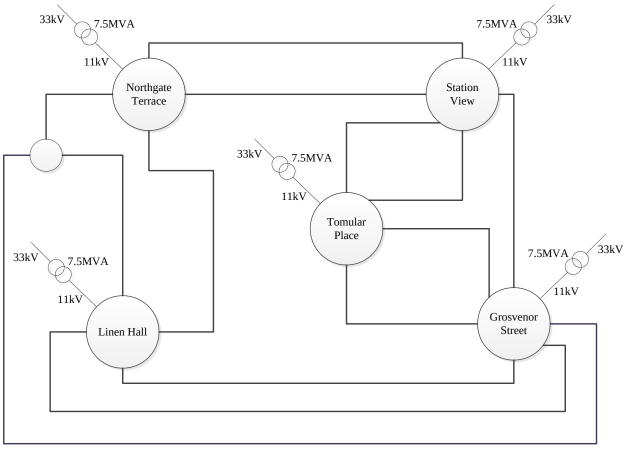

Figure 3 Chester City Centre 11kV Network

The Chester network is an ideal trial site for the RTFLM for a number of reasons:

I. It is perceived to be operating close to the 250MVA (13.1kA) fault level design limit for the 11kV network. Trialling the RTFLM in the group will also potentially lead to the release of network capacity.
II. This network provides an opportunity to assess the maximum size, duration and frequency of synthetic disturbances required to generate reliable results.
III. As the network can operate securely with 4 of the Primary substation transformers in operation, it provides the opportunity to vary the fault level in real time by switching one of the transformers in and out of service. Tomular Place was chosen as the candidate transformer to be switched.
IV. SPEN and ORL have previous experience of monitoring this network using a Natural Disturbance FLM. Results from both approaches can be cross validated against each other.

Station View Primary Substation Installation

Station View was identified as the preferred Primary substation for the trial against the following criteria:

- Ease of access to the secondary wiring of the 11kV busbar Voltage Transformer (VT)
- Ease of access to the LV distribution board coupled to the 11kV busbar by a local 11kV/LV secondary transformer.
- Availability of space to host the RTFLM

The RTFLM was physically installed in the substation in October 2018 (**Figure 4** below). For convenience the LV board connection was made with heavy duty flexible cables with quick release Litton Veam connections, the same type of connection used for emergency generators. The VT wiring was achieved using small diameter armoured cable with 4mm plug connections to the front of the RTFLM.

Figure 4 RTFLM Installed at Station View Primary

Modelled Fault Level

Ahead of live trials the network was modelled using SPEN's approved design tool, IPSA, to ascertain the expected 11kV fault level at Station View. This analysis indicated the fault level values shown in **Table 1**.

11kV Fault Level at Station View	10ms Make Fault Current	90ms Break Fault Current
As 5 Group (with Tomular Place transformer in service)	27.49kA	12.92kA
As 4 Group (with Tomular Place transformer out of service)	24.80kA	11.55kA

Table 1 IPSA Modelled Fault Level at Station View Primary

PRELIMINARY RESULTS

Prior to the Chester trial various simulation scenarios had been tested at LV, 11kV via 200kVA and 500kVA distribution transformers, and also 33kV via 33kV/11kV and 11kV/415V transformers. Different source impedances, X/R ratios and transformer loading conditions have been tested, all suggesting that given a clean 33kV or 11kV network, results for typical fault levels (1000MVA at 33kV, 250MVA at 11kV) can be obtained in line with the target criteria. The real world trial was approached with some confidence.

December 2018 Tests

Initial results were obtained for the prospective 90ms RMS break fault level for the Station View substation 11kV busbar. At the time the Chester Network was being run as a 5 group, and at this site the in-service 500kVA distribution transformer was used for the LV to 11kV disturbance coupling.

Artificial Disturbances Applied

The LV disturbances were created at different rates and lengths, with the concentration on use of 4 inductors (load of 5mH), and duty of short and long pulse intervals of 290ms, and 1910ms respectively. Pulse length was nominal 9.4ms. (These lengths were chosen somewhat arbitrarily to ensure that the conservatively set thermal safety trip points would not be reached.)

Figure 5 shows the LV current injection between phases A and C.

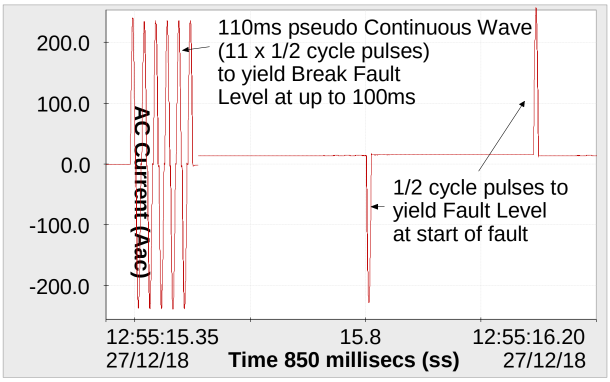

Figure 5 LV Current Injection between Phases A and C.

Effects on the Network

The effect of this on the 11kV is shared between V_{ab} and V_{ac}, (Transformer is vector group DYn11). **Figure 6** shows (from top to bottom) V_{ca}, V_{ab}, V_{bc} at 11kV, and V_{ac} at LV.

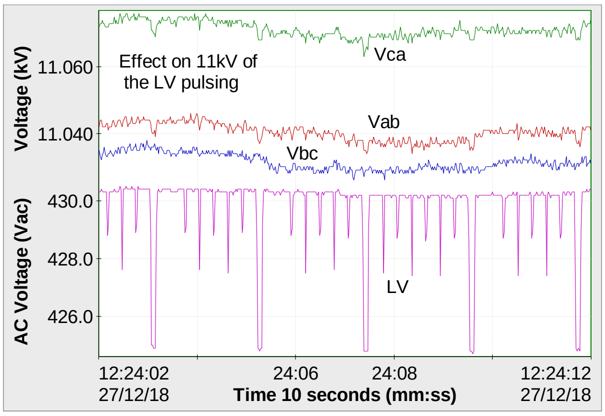

Figure 6 Voltage Response to Artificial Disturbances

The effect at LV is a pronounced depression of 5.6V (1.3%) for the 110ms pulse, but at 11kV, the same pulse drops the voltage by just 0.03% (~3V). The short pulses are indistinguishable from underlying noise.

Consequently Flicker at 11kV, already very low at this site, is barely affected (Perceptibility Short Term (P_{st}) ~0.14). Total Harmonic Distortion (THD) is <1%. At the same time as the prospective fault level and voltage power quality at 11kV were measured, the effects on the LV distribution service was also recorded. Flicker P_{st} degraded to 1.58 and 0.98 on V_{cn} and V_{an} respectively.

V_{bn} was not affected. (The P_{st} difference on V_{cn} and V_{ab} is due to the relative phasing of normal load with the additional phase-phase inductive load.). THD remained low (~1.6% on all three phases).

Results Obtained

The prospective RMS break fault level at 90ms was measured at 12.98kA, <0.5% higher than the modelled 12.92kA value for the same network running arrangement listed in **Table 1**. This result is obviously very encouraging for the future of this project.

Assessment of Errors

The above result was obtained from the average over >10 minutes. In fact significant variations sometimes approaching ±4% were observed within 30 seconds of each other. Whether this is due to instrumentation/network noise rather than actual variation of fault level is under investigation. There are several potential sources of error.

Noise or interference may be classified into white random Gaussian (which can be averaged out), slow but incoherent systematic noise, e.g. interharmonics, whose effect may endure in the short term but will average out long term, and coherent systematic interference which will permanently bias the results, e.g. voltage pick-up on sensitive VT signals due to the high LV current pulses. Transducer performance (including processing algorithm) has a direct bearing on results without introducing tell-tale noise.

Network effects

There may also be low level network effects not normally visible or included in static fault level models. Some consistent anomalies in voltage response over time (ms) have been observed, and their legitimacy is a subject for future work.

POTENTIAL ROLE OF REAL TIME FAULT LEVEL MONITORS

The number and range of potential network applications that RTFLMs have is genuinely exciting. First and foremost they have a role in addressing one of the biggest challenges facing DNOs but they also have the potential to do so at a pragmatic cost. The expected cost of the RTFLMs is magnitudes lower than the cost of traditional network reinforcement, in most cases they would only need to release a small amount of network capacity to facilitate the connection of LCT.

Adopted, RTFLMs have the potential to offer DNOs and customers a number of benefits. They will facilitate:

- Increased safety of persons in proximity of the network by reducing the risk of assets operating above design limits
- Increased operability / security by providing DNOs with data that will allow greater interconnection
- Refinement of models to release additional firm capacity
- The introduction of Active Network Management allowing customers to access un-firm capacity identified
- Faster / cheaper connections for customers, increasing the uptake of LCT
- Greater visibility / understanding to DNOs fault level of the network, seasonal variability and contribution from customers

NEXT STEPS

The performance and results obtained to date from the Chester trial have been very encouraging. Further tests and trials are required to validate the performance of the unit to deliver reliable 10ms make fault level results and observe the change in results for the group when Tomular Place is switched out. Trials of a second prototype RTFLM will also take place. The results to date have been successful enough for SPEN to start drawing up plans for how the technology can be transitioned to Business as Usual (BaU).

33kV Trials

For SPEN the biggest potential application and business case for the RTFLM is at 33kV. Consequently it is essential that the next trial phase also examines the performance of the RTFLM at this voltage. Several constrained 33kV substations have been targeted for trials of the RTFLM in early 2019. These trials will identify the suitability of the synthetic disturbances to generate reliable and repeatable results.

National Pilot Project

Beyond the 33kV trials, assuming continued success, the next logical step is to undertake a large pilot project in partnership with other UK DNOs. This project is still evolving, but it is expected to include a high volume of RTFLMs deployed across the UK on fault level constrained networks and SCADA integration. The purpose of these trials will be to fully assess the benefits that the RTFLM introduces to DNOs and customers.

It is envisaged that this project will take place utilising Ofgem’s Network Innovation Allowance (NIA) funding. A project start date is earmarked for mid-2019.

REFERENCES

[1] “Innovation Funding Incentive Annual Report 2010/2011, SP Energy Networks”, (Glasgow, Scotland)

[2] J. Berry, S. Jupe, M. Meisinger and J. Outram, 2013, “Implementation of an Active Fault Level Monitoring System for Distributed Generation Integration”, CIRED 2013, Paper 0619.