VALIDATION OF A FAULT LEVEL MEASUREMENT ALGORITHM FOR ELECTRICITY NETWORKS

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ABSTRACT

For electricity distribution networks, fault level management remains one of the greatest challenges to overcome in the transition to Net Zero. The rapid growth of low carbon technologies, such as distributed renewable generation or electric vehicles, will dramatically increase the exercising of distribution systems, potentially stressing the networks beyond the intended design. Innovative solutions that enable active fault level management are therefore essential for network operators to ensure any fault current remains within safe design limits, by obtaining high quality data of network characteristics.

The Real Time Fault Level Monitor (RTFLM) is an attractive solution to enable electricity Distribution Network Operators (DNOs) worldwide to safely accept new connections, potentially without or by reducing/deferring the need for disruptive and costly network reinforcement. This paper discusses Outram Research's development of the RTFLM device, with particular emphasis on the rigorous testing that has been completed to date with two UK DNOs, SP Energy Networks and UK Power Networks, and explores the benefits of deploying this technology to overcome the fault level challenges associated with Net Zero.

INTRODUCTION

Net Zero targets are driving unprecedented growth in the use of Low Carbon Technologies (LCTs), led by the rapid growth in uptake of Electric Vehicles (EVs) and distributed generation. This has created a particularly challenging environment for DNOs to provide timely, low-cost network connections whilst ensuring the safe design limits of the distribution system are not exceeded.

Fault Level (FL) is the term used to describe the maximum current that will flow through an electrical system under short circuit, or fault, conditions. The amount of current is dependent upon the voltage and impedance to the fault at the time and can range from hundreds of Amps (A) in a standard domestic electrical installation, to many thousands of Amps in large industrial power systems. Connected load (such as motors or EV charge points), network configuration, transmission and distributed generation all contribute to system FL and the energy released in a short circuit condition.

Safety is paramount for network operators; knowing the FL at every point on the network is critical for operators to keep it within safe limits. These limits reflect the design rating of electricity assets, such as switchgear, cables, and transformers, and must not be exceeded. Any current in excess of the FL rating poses a significant risk of damaging valuable equipment and to public safety. Conversely, some FL is a necessary operating characteristic of electricity networks - should the FL be too low, then critical protection equipment may fail to operate. For these reasons, FL needs to be operationally managed to within an acceptably safe range.

Active FL management is therefore essential for DNOs to remain key enablers of LCTs and the Net Zero transition. The management of FL can only be delivered with high quality knowledge of network characteristics. Traditional assessment methods, such as offline network modelling, can restrict the capacity of existing networks to accept new connections due to a lack of real-time FL fluctuation visibility and deliberately conservative calculations given their high dependence on external information sources. FL management is therefore one of the most pressing challenges for DNOs, and solutions are required to cope with fast increasing demand while ensuring high quality levels of service and resiliency.

This paper presents the background to this work and discusses Outram Research's Real Time Fault Level Monitor device (RTFLM) as a solution to help with this challenge, including the rigorous testing that has been undertaken to validate its performance.

THE FAULT LEVEL CHALLENGE

DNOs worldwide need to stay one step ahead of changes in consumer behaviour. The Climate Change Committee (CCC), the UK's independent advisor for tackling climate change, emphasised that the full transition to EVs is one of the most important actions to achieve Net Zero targets [1]. Through Distribution Future Energy Scenarios (DFES), SP Energy Networks forecast their network may have up to 1.8 million EVs by 2030 [2]. In the same time period, UK Power Networks forecast up to 4.5 million EVs, 30 times more than are connected today [3]. At the same time, the traditional, simplistic, top down model of large synchronous (fossil fuel) generation, that represented a relatively stable and predictable network based on unchanging infrastructure properties, is now making way for more highly utilised networks connecting with smaller-sized Distributed Energy Resources (DER) of varying generation characteristics. This growth in generation complexity, combined with the electrification of mobility, creates a network not only with an unpredictably increasing load but with a dynamic electricity load curve exhibiting peaks and troughs driven by electric vehicle hotspots, most notably within suburban areas.

In this rapidly evolving environment, DNOs have a legal obligation to provide timely connections while, as previously stated, remaining safely within the design limits of the network. These connection decisions are all driven by the ever-shifting FL capacity of the network. Traditional FL management, such as reinforcement works needed to increase the FL handling capacity to accommodate new import or export connections, represents a major obstacle to achieving Net Zero targets by impeding timely and cost-efficient connections. We need new tools and innovative solutions to transform the networks so they can overcome the potential barriers posed by traditional FL management, and facilitate these LCTs.

A REAL TIME FAULT LEVEL MONITOR SOLUTION

Developed by Outram Research, a leading design house and manufacturer for Power Quality and Fault Level devices, the RTFLM is the first ever compact unit capable of measuring Peak and RMS prospective short-circuit current in real time at 11kV and above. This presents a ground-breaking opportunity for DNOs to proactively identify available capacity on the network, and to improve our understanding of static and dynamic network constraints. The improved visibility of network FL will allow better informed decisions to be made, enabling us to accommodate and, where appropriate, to manage more network connections while triggering fewer equipment replacements or network reconfigurations. Where necessary, we can embark with greater certainty upon reinforcement programmes to facilitate e-mobility and the energy transition.

Outram Research and SP Energy Networks have been incrementally developing the solution since 2010 to gain visibility into FL through measurement rather than computer modelling, first with passive measurement devices and subsequently with active devices to obtain results continuously in real time [4] [5]. Following initial demonstrations, the project has now extended into more extensive trials bringing on UK Power Networks as a project partner.

A description of how the RTFLM operates has been published previously [4]. In short, the device measures and collates the network response, represented as voltage and current changes, to network disturbances and (after filtering to remove natural noise content) obtains a FL value. The RTFLM uses its own disturbance generator to provide a measurable voltage network response at the target bus, overcoming the dependency on naturally occurring network disturbances which may or may not be present, and therefore reduces the time to produce a quality result from weeks as with the passive device, to seconds.

When deploying any innovative, ground-breaking technology, it is critical to ensure the new method is both accurate and an improvement on the previous method. In the case of the RTFLM, this required independent verifications of the fault level measurement algorithm. Confirming algorithm fidelity provides the confidence in the measured vs modelled results. Without such verification, differences between the two methods for determining fault level would be difficult to evaluate.

To address this need, two test methods of increasing cost and significance were undertaken at two specialist test facilities: firstly, the Power Networks Demonstration Centre (PNDC), in Scotland, made nearly 60 measurements and evaluated FL values for multiple network topologies using a Real Time Digital Simulator (RTDS) as a controlled substitute for the network; and subsequently at VEIKI-VNL laboratories in Hungary, FL predictions from the RTFLM were compared with real fault current measurements at up to 36kV.

The results of this extensive testing are discussed in this paper, together with further lessons learned. These results are fundamental to realising the benefits of real time FL monitoring on electricity networks around the world and to reduce the costs associated with the Net Zero transition.

REAL TIME DIGITAL SIMULATOR

The first approach to evaluate fidelity of the fault level measurement algorithm was to use an advanced RTDS at the PNDC.

The RTDS gave opportunity for multiple network configurations to be designed and simulated in complete safety within a relatively short time span. The RTDS simulated a virtual network, based on a section of real network created by using information supplied by SP Energy Networks. Changes could be made to the virtual network, such as the connected location of the RTFLM load disturbance generator, or by adding network interconnection downstream of the measurement node.

The stripped-down RTFLM was looped into the test setup as part of a controller hardware-in-the-loop configuration. A digital input card received the stimulating signals from the RTFLM. The RTDS then simulated the inductive pulses and the network's response and the output data from the RTDS was then fed into a Digital to Analogue Converter (DAC) card. The DAC output signal was then fed back to the RTFLM to provide the voltage changes observed on the virtual network.

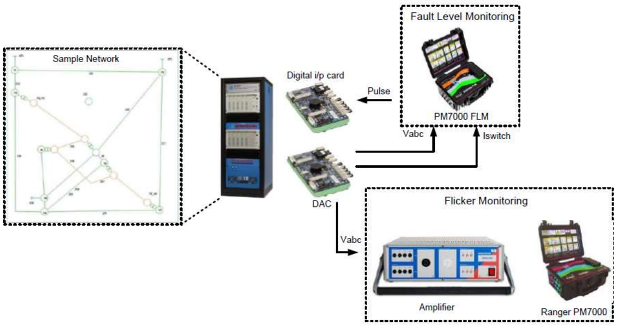

Figure 1: Controller hardware-in-the-loop configuration utilised at the PNDC

A further output stream was connected via an electronic amplifier to a second, independent power quality logger to measure flicker levels. This configuration is illustrated in Figure 1. The network model used was based on a section of network consisting of three 132kV grid supply points. The supply points utilised 60MVA transformers feeding an interconnected 33kV network which in turn utilised multiple 33/11kV transformers with a capacity of up to 10MVA to feed further interconnected networks at 11kV. Simulations and subsequent results were measured across three voltage levels and in various locations. The locations accounted for interconnection and direct coupling capability, testing 59 configurations in total.

With the results from the simulations the data was used to assess the following:

- Accuracy of RTFLM results – testing to validate the accuracy of the RTFLM against the RTDS model's results.
- Flicker analysis – an independent recorder connected to test for flicker caused by the RTFLM disturbance generator.
- Speed of response – to test the speed of response from the RTFLM in providing fault level data.

A report detailing the results of this work has been made publicly available [6], with key findings as follows:

Accuracy

The ability of the RTDS to easily modify network topology and connection methods permitted experimentation with various different options for the electrical coupling of the LV disturbances to the target bus, and the effect of any further network interconnections on the measurements obtained. The purpose of this work was to improve understanding as to how the device should be deployed on real networks in the future. Whilst interconnection below the target bus can have an effect in diluting the results, this work demonstrated that this can be overcome by having a direct coupling from LV to the target bus. This allows all of the fault current contribution to be measured as it cannot be fed from any other means.

Results showed the fault level algorithm fidelity to be extremely accurate when a direct coupling is made; differences were below 1.5% for both Make and Break at 11kV and similarly below 2.5% at 33kV.

Flicker analysis

The RTFLM disturbance generator utilises a bank of inductors. Power electronic switches are used to rapidly connect and disconnect this inductive load at LV to create a disturbance. The disturbances are required to accurately measure FL, however in a scenario whereby the LV feeder to which the disturbance generator is connected is also supplying customers, quality of supply must be maintained as per recommended guidelines ENA P28 and G5/5 [7]. For this reason, different inductor and power switching sequences were evaluated to analyse the effect on flicker.

Results confirmed that a reduction in inductance value will increase the flicker, as will an increase in the pulse duration. This evidenced that the RTFLM was capable of keeping within flicker guidelines, by reducing the number of inductors or the pulse rate and width, or both. For real network deployment, the option taken will be dependent upon the characteristics of the section of network being monitored.

Speed of response analysis

The PNDC created a scenario in which a Grid Supply Point (GSP) was disconnected followed by reconnection. The RTFLM responded within 7.5s and 12.5s to the disconnection and reconnection respectively.

LIVE FAULT LEVEL TESTING

The purpose of the full-scale live tests was to examine the ability of the RTFLM to correctly predict the network FL under different source impedance conditions and different busbar voltages representative of normal electricity distribution network operation. The actual fault current present was to be measured following full bolted faults at the target busbar.

Finding a suitable facility was challenging, because it is difficult in practice to deliberately induce real faults onto live distribution networks. Following extensive research, the VEIKI-VNL Electric Large Laboratories Ltd in Budapest, Hungary was identified as a suitable facility because their test network was energised by the Hungarian grid, and hence was more representative of true distribution network operation than the more common generator-based fault creation facilities. They were also able to offer faults at a variety of voltages.

The 132kV grid supply was transformed down to the target bus voltages to which the laboratory was able to apply bolted faults. The maximum FL available was ~150MVA. The bus voltages and available fault currents are shown in Table 1.

Table 1: Bus voltages and available fault currents available at the VEIKI-VNL Electric Large Laboratories Ltd. in Budapest, Hungary.

Target Bus Voltage (Nominal)	Maximum Fault Current available (RMS)
10.5kV	7.4kA
36.4kV	2.2kA
31.4kV	2.2kA

The fault protection circuit breakers were set to operate after 300ms, so fault current at 90ms could be readily observed. The laboratory was able to change the physical source impedance conditions for each of these voltages to test a variety of fault levels at the different bus voltages. Similarly, the RTFLM loading could be altered to test different disturbance levels for the prediction process.

The RTFLM, operating as described in the literature [4], was connected at LV (~400-415V) to the secondary side of a coupling transformer, whose primary side was connected the target bus, this is illustrated in Figure 2. In summary, the coupling arrangements used are listed in Table 2.

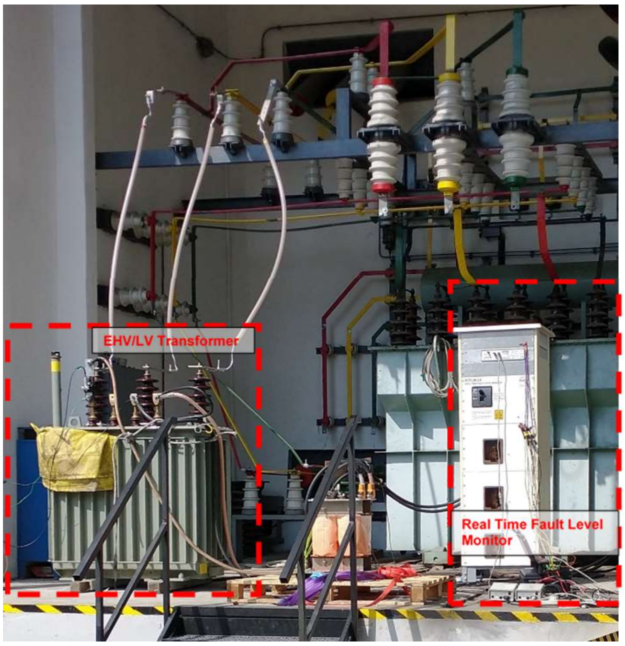

Figure 2: Test set up at the VEIKI-VNL Electric Large Laboratories Ltd. in Budapest, Hungary.

For the 10.5kV and 36.4kV target bus tests, a single distribution transformer was used to provide the coupling. The 31.4kV tests were included to demonstrate the effect of two coupling transformers in series.

Table 2: Coupling arrangements used

Target Bus Voltage (Nominal)	Coupling Transformer rating	Available LV
10.5kV	1000kVA Distribution Transformer	410V
36.4kV	250kVA Distribution Transformer	412V
31.4kV	250kVA, followed by 100kVA Transformer	424V

Test performed / Description of the tests

The tests were performed in two parts: prediction (where the RTFLM was involved); and actual fault current measurement (by the laboratory, not involving the RTFLM device).

The network connection with the chosen source impedance at the target bus voltage was energised and the RTFLM operated for a short period (minutes) to measure the source impedance and hence predict the FL for half-cycle Peak (Make) and 90ms RMS (Break). The average target bus voltages were measured during this time.

A bolted fault (referred to in the laboratory parlance as a “shot”) was then applied on the target bus under the same source impedance conditions, and the fault current measured using the laboratory instrumentation. The target bus voltage immediately prior to the bolted fault application was also measured, to consider voltage variation between prediction and actual values when comparing predicted and measured fault currents.

During the tests, consistency of results was examined both for the laboratory fault current measurement, and for variation in RTFLM loading. To test the laboratory’s actual FL consistency and that of the laboratory instrumentation, multiple “shots” were performed on an unchanged installation. Some variation was to be expected for various practical reasons. In practice, the RMS results were very consistent (<0.6% spread), but due to significant (and variable) pole scatter within the laboratory circuit breaker, Peak half-cycle results were less consistent.

Algorithm Performance

Figure 3 shows the results achieved across 14 tests. The average difference in magnitude between prediction and measurement for RMS FL at 90ms was 0.78%, with a worst case of 1.61%.

Referring to Figure 3, tests 1, 2, 3, 4, 8, 12 were performed with the nominal 10 inductors in parallel (maximum load). Tests 5 and 9 were with four inductors, and tests 6, 7, 10, 11, 13 and 14 were with two inductors in parallel.

Results from the RTFLM prediction for Peak FL (Make) were also consistent, with Peak FL for the same source impedance but with different numbers of inductors differing by < 1%, however the pole scatter present on the breakers creating the bolted fault significantly affected the Peak currents measured.

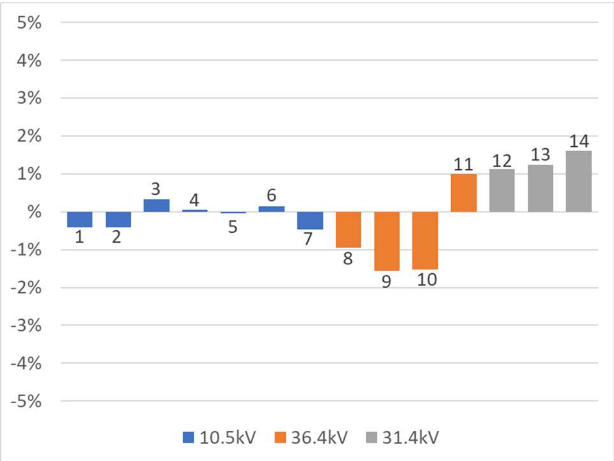

Figure 3: Comparative distribution (%), RMS prediction at 90ms compared with laboratory measurements for each test (numbered 1-14)

Variability characteristics of pole simultaneity for circuit breaker operation are anticipated within IEC 62271-100 and therefore some pole scatter can be expected. Other considerations affecting measured Peak results include different point-on-wave "shots", and any FL unbalance and voltage variation between phases. Evaluation of the influence these considerations might have on how the measured FL values will be used in practice is ongoing and consequently it has not yet been possible to make a meaningful comparison between the predicted Peaks from the RTFLM (which assumed zero pole scatter) and the laboratory measured results. Further work is in progress to process the raw data from the laboratory to extract more refined Peak results, and hence to reduce the uncertainty in a realistic assessment of the RTFLM's Peak prediction accuracy. Nevertheless, the results to date continue to demonstrate significant promise.

CONCLUSIONS AND FURTHER WORK

This paper has presented further progress of ground-breaking innovation to enable the measurement and continuous monitoring of electricity distribution network Fault Level (FL) in real time.

The ability to measure actual FL will significantly improve our understanding of network constraints and will allow better informed decisions to be made. To transition this technology from trials to business as usual application, it was necessary to demonstrate that the RTFLM solution is both accurate and an improvement on the previous method through independent verifications of the FL measurement algorithm. Two approaches were used: firstly, using a Real Time Digital Simulator (RTDS) as a controlled substitute for the network; and secondly, using a live network test facility where it was possible to compare actual fault current with the measured fault current predictions.

Results from use of the RTDS showed the FL algorithm fidelity to be extremely accurate when a direct coupling is made; comparative results were below 1.5% difference for both Make and Break at 11kV and similarly below 2.5% at 33kV. Results from the live test network demonstrated an average difference magnitude between prediction and measurement for RMS FL at 90ms of 0.78%, with a worst case of 1.61%. In all cases, these results are an improvement on the original project aims of 5% for algorithm fidelity.

Further work is ongoing to fully understand the influence some of the broader findings will have on how the measured FL values will be used to replace or complement existing methods. The results of this work continue to be extremely positive making the RTFLM a particularly favourable solution for the management of FL for electricity distribution networks worldwide.

REFERENCES

[1] T. Wills, 2020, "The UK's Transition to Electric Vehicles", Climate Change Committee.

[2] SP Energy Networks, 2021, "Distributed Future Energy Scenarios", *SP Energy Networks.*

[3] UK Power Networks, 2021, "Distributed Future Energy Scenarios", *UK Power Networks.*

[4] G. Murphy, J. Outram, R. Bryans, et al. "Real Time Fault Level Monitoring", *CIRED Madrid 2019*

[5] M. Khaddoumi, J. Outram, R. Eyre-Walker, et al. "Real Time Fault Level Monitoring for Network Capacity Management", *Cigre Paris 2020*

[6] University of Strathclyde, Power Networks Demonstration Centre, 2020, *"PNDC Testing of the Outram RTFLM – Final Report"*

[7] Energy Networks Association, 2020, "Engineering Recommendation G5 Issue 5 2020, Harmonic voltage distortion and the connection of harmonic sources and/or resonant plant to transmission systems and distribution networks in the United Kingdom"