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EXPLAINS

Prospective fault level monitoring

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Contents

Introduction

It is now possible to measure the prospective short circuit current or fault level on electrical networks up to 33kV in real time, with no computer modelling involved. This is actual measurement of the prospective fault level, through voltage transformers and current transformers, without any need to introduce a fault on the network. The monitoring equipment has been developed by UK technology business Outram Research – in a project led by SP Energy Networks – by building on its expertise in signal processing. With the potential to fundamentally speed up investigations on network capacity, and create confidence in investment and connection decisions, its Real Time Fault Level Monitor could make a critical difference to network operators as they seek efficiencies and the faster connection of renewables. This special supplement describes the backstory to a true innovation in the sector, and how networks at the leading edge are already taking advantage of it.

What is fault level?

Fault level, also referred to as short circuit current, is the highest amount of current that might flow in an electrical system under short circuit conditions; the actual amount of current is determined by the voltage and impedance to the fault at the time. In energy terms, the power available under fault conditions could be in the range of hundreds of kVA in a standard domestic electrical installation, to thousands of MVA in large industrial power systems.

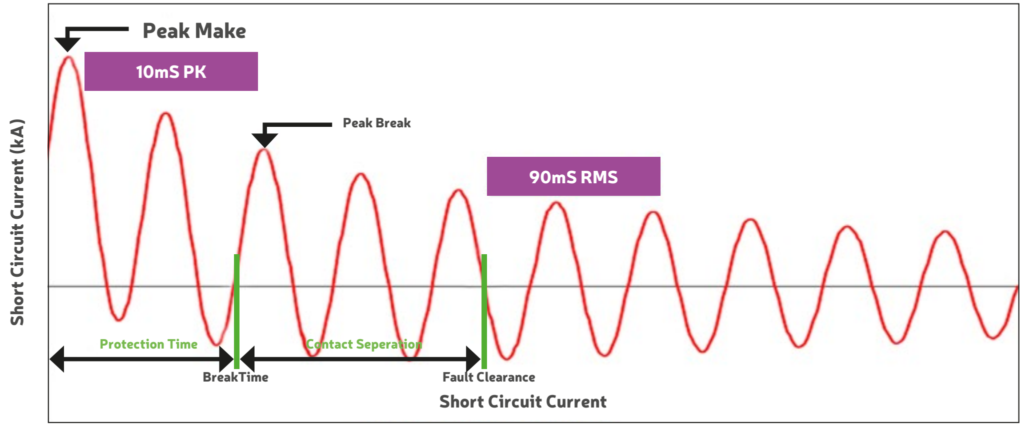
Kate Edwards, sales and marketing manager at signal processing specialist Outram Research, offers some analogies: “In fault conditions, you might get 250 MVA of short circuit power in an 11kV network – that’s equivalent to the energy used by a jumbo jet on take-off or to make 250,000 cups of tea.”

> We need innovation to remove these blockers and become a low carbon network - it’s key to our transformation
>
> **Ralph Eyre-Walker, SP Energy Networks**

At each substation or customer connection, any current in excess of the fault level rating assigned to fuses or circuit breakers risks damage to valuable plant and equipment – not to mention posing an obvious safety risk to any personnel in the vicinity. For electricity distribution companies, called Distribution Network Operators (DNOs) in the UK, knowing the appropriate fault level at every point on the network is therefore critical to safe and secure network management. Accurate fault level data ensures that network equipment is specified or installed with sufficient capacity to protect investment, supply and personnel.

In the ongoing drive to add renewable generation and create “flexible” networks, fault level becomes a particularly crucial operating parameter. If there is little headroom between the projected fault level and the design limits of the network’s plant, cabling and equipment, then reinforcement works – adding cost, complexity and delays – would be necessary to increase the fault level handling capacity to accommodate additional import or export connections. Conversely, if the prospective fault current is substantially below the network protection settings, the system becomes vulnerable to power quality issues. Potentially, in the worst case scenario where a fault does not trip the breakers or other protection equipment, the network would be rendered unsafe.

SP Energy Networks: fault current wave shape



Traditionally, fault level has been calculated using software modelling tools, which calculate a projected level based on the voltage and impedance data gathered from suppliers, manufacturers, customers and generators. But these projections are only as accurate as the input data – which may be misstated, miscalculated or have changed over time – and has to be constantly updated to come close to the accuracy that today’s network operators need.

While DNOs used to manage a one-way power flow, distributing power from the national transmission grid to their customers, they are now accommodating increased local generation on their networks. At the same time, demand is increasing, as growing networks of electric vehicle (EV) charging points, electrified heating systems and more consumer demand draw more power from the networks. Many DNOs and large industrial customers have realised that evolving networks need new tools to assess fault level, and the network capacity that hinges on it.

At SP Energy Networks, the DNO for central and southern Scotland, Merseyside, Cheshire and north Wales, senior innovation engineer Ralph Eyre-Walker explains the impact of higher demand and renewable generation on its network. “The combination of both factors pushes the fault level on the network higher, and, as the fault level limits on the switchgear are reached, the fault level is becoming a potential blocker as we make the transition to becoming a Distribution System Operator (DSO). We need innovation to remove these blockers, so that we can facilitate a low carbon future– it’s key to our transformation.”

Early work on fault level monitoring

In fact, SP Energy Networks foresaw that challenge around a decade ago, an insight that led the DNO into discussion with Outram Research, a manufacturer of power quality meters and measurement devices for a range of industries. In 2010, the two companies jointly embarked on a project to develop a device that could physically measure fault level. While the industry relies on software modelling of these values, an accurate measurement device would allow the DNO to know whether it had over- or under-estimated this important safety parameter. Its data could be used to verify the prospective fault levels calculated by software models, allowing SP Energy Networks and other DNOs to have greater confidence in adding new connections or embarking on reinforcement programmes.

The first fruit of their collaboration was the world first PM7000 Power Quality and Fault Level Measurement device, known as the PM7000FLM. Launched in 2011, it became a double finalist at the Electrical Industry Innovation Awards 2012.

Once installed, on a radial network, it works by taking advantage of natural disturbances in the current flow having a direct effect on the voltage. It measures the response of the key parameters in great detail, and from these can accurately calculate the fault level.

The monitor depends on the level of natural disturbances, rather than actual "faults" on the network. These can be caused, for instance, by power-hungry motors or industrial fridges being switched on and off. This means that the equipment may need to be in place for up to two to three weeks before enough data is gathered.

The PM7000FLM has been used successfully at 132kV, 33kV and 11kV, and is especially well suited to lower voltage radial networks. At Outram Research, managing director John Outram explains: "Among other places, the PM7000FLM was successfully trialled in Chester in 2013 (*see page 9*) where it enabled the use of an additional transformer on an 11kV interconnected ring thought to be constrained by fault level capacity. The projected cost of reinforcing that part of the network, in order to incorporate that transformer, to improve the quality and security of supply, was in the region of £250,000. This compares to the outlay on a single, reusable, portable FLM at just a few percent of this amount."

Where distributed generation as well as new types of demand loading are a factor, DNOs will often require a real-time reflection of what's happening on their network. In 2016, SP Energy Networks and Outram Research committed to developing a "Real Time Fault Level Monitor" to generate results in real-time, up to date within seconds. The monitor was also designed to be suited to the higher voltages of the main distribution networks.

After a successful "proof of concept" trial in Chester in 2019 (*see case study 2*), where measured results proved to be very close to the models, the RTFLM device will now enter a second phase of trials.

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>
> **John Outram, MD, Outram Research**

Outram is currently manufacturing another 20 units. The RTFLMs will be put to the test in ten SP Energy Network areas with constrained fault level, in both its Manweb and Scottish Borders licence areas. A second DNO, due to join the project in H1 2020, also hopes to be participating, bringing to the trials the benefit of its densely inter-connected, urban licence area.

"We're moving into the second stage of trials with SP Energy Networks to put RTFLMs into a broad range of substation scenarios, so we can observe them working in various set-up configurations," says Kate Edwards at Outram Research. "Every substation is different, so it's a case of installing RTFLMs into as many different scenarios as is feasible. For SP Energy Networks, our technology is 'top of the list', they think it's hugely exciting."

At UK Power Networks, innovation lead Ian Cooper is watching with interest. "Having utilised the portable PM7000FLMs with success, we are keen to see the outcome of this trial and the potential of being able to apply the RTFLMs to our network. They are a viable solution in the many situations where real time fault level results would allow us to run our network more safely, connect more generation at lower cost and provide a better service to our customers."

Why is fault level critical to safety?

Health and safety is another important driver for accurate fault level measurements. When a high voltage is switched with large current available, there may be a significant arc flash. This could seriously injure any personnel in the vicinity, as well as cause damage to equipment or start a fire.

While the general risk of arc flash is well known, the hazard will not be constant at all places on the network. Variations in fault level at different points could mean that installations, and the personnel working on them, have the wrong level of protection. Another scenario – in cases where the fault level ratings have been set too high – is that a short circuit can smoulder, without tripping the fuse or circuit breakers. As the current flows unimpeded, fire or explosion risk escalates rapidly.

Edwards notes that applying a blanket fault level rating, with a lack of differentiated data, is often a weak point in any safety management strategy. "It's important to know the short circuit current at the place you're working. The quoted fault level that people work to is often defined at the 'point of common coupling', the point in the electrical system where cable or infrastructure ownership or responsibility levels shift from the utility to customer. The fault level on the customer's network is often extrapolated from that, but it may not be as accurate as you would want," she notes.

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> **Kate Edwards, Outram Research**

Why is fault level important in the era of renewable generation?

For today's rapidly evolving networks, where DNOs have a legal obligation to provide timely connections while ensuring that the design limits of plant and equipment are not exceeded, fault level management is a key operational issue. Connecting new distributed generation to the network increases the local fault level, so the network's fault level rating limits the amount of distributed generation that can be connected. This is most likely to be a problem in dense urban areas where generation is likely to come from combined heat and power plants or diesel standby generators, which typically have a high impact on fault levels.

As Edwards summarises: "System generation is no longer top down, and as a result modelling has become far more complicated. Networks have started pushing at the boundaries of fault level ratings. The more renewable generation is connected, the greater the risk that the fault level goes above the limit," she says. "The DNO can't make connections if they haven't got the capacity to add new generation. We need to find technology to allow the DNOs to connect renewables without unnecessary spending on network upgrades."

The causes of short circuits are also changing. Whereas traditionally it might be an object falling on an overhead line, a cable strike or a mechanical fault, today's issues include short circuits in inverter-based renewables generation sources. Renewable sources, generating direct current (DC) electricity that is then converted by an inverter to grid-compatible AC power, are more likely to "stall" than synchronous generators, thereby creating a short circuit and power outage.

Meanwhile, over long, extended networks, the customers at "the end of the line" may have a fault level lower than they are expecting. That can bring its own problems: for instance, an industrial customer might not be able to restart production line motors after an outage due to inadequate start-up power availability. A motor can draw up to six times its normal running current, or more, while starting, so a large and sudden electrical load can be a problem where there is a low fault level.

"If the fault level is too low, motors may not be able to start up," says Edwards. "Or if the short circuit current level isn't known, you're operating in the dark. Can you safely switch back on? Conversely, if the fault level protection rating is set too high for the available fault current, the protective devices may switch too slowly, or not at all."

While a low fault level is most likely to be the problem outside built-up areas, city centres are often identified as operating close to fault level safety ratings. Where there is perceived to be little headroom between the current and fault level limits, the risk of overloading the network could prevent new customers, battery storage or generators from being connected. In addition, most networks add in a margin of safety – which could artificially depress connection capacity.

Knowing fault level is also critical to complying with guidance published by the Energy Networks Association, EREC G5/4, "*Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom*". This is because higher levels of current harmonics can be acceptable if the network fault level is high, a factor that can now also be recorded during the harmonics week-long survey. "It might pay to know exactly what your fault level is – it may mean you don't need the harmonic filter you might otherwise have thought you did," explains Edwards.

Installing an RTFLM device in the nearest substation could identify enough (although not necessarily continuous) fault level headroom to facilitate new customer connections in scenarios where the fault level is constraining capacity. Real time fault level data can also boost DNOs' visibility of seasonable variability.

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> **Kate Edwards, Outram Research**

The role of software modelling

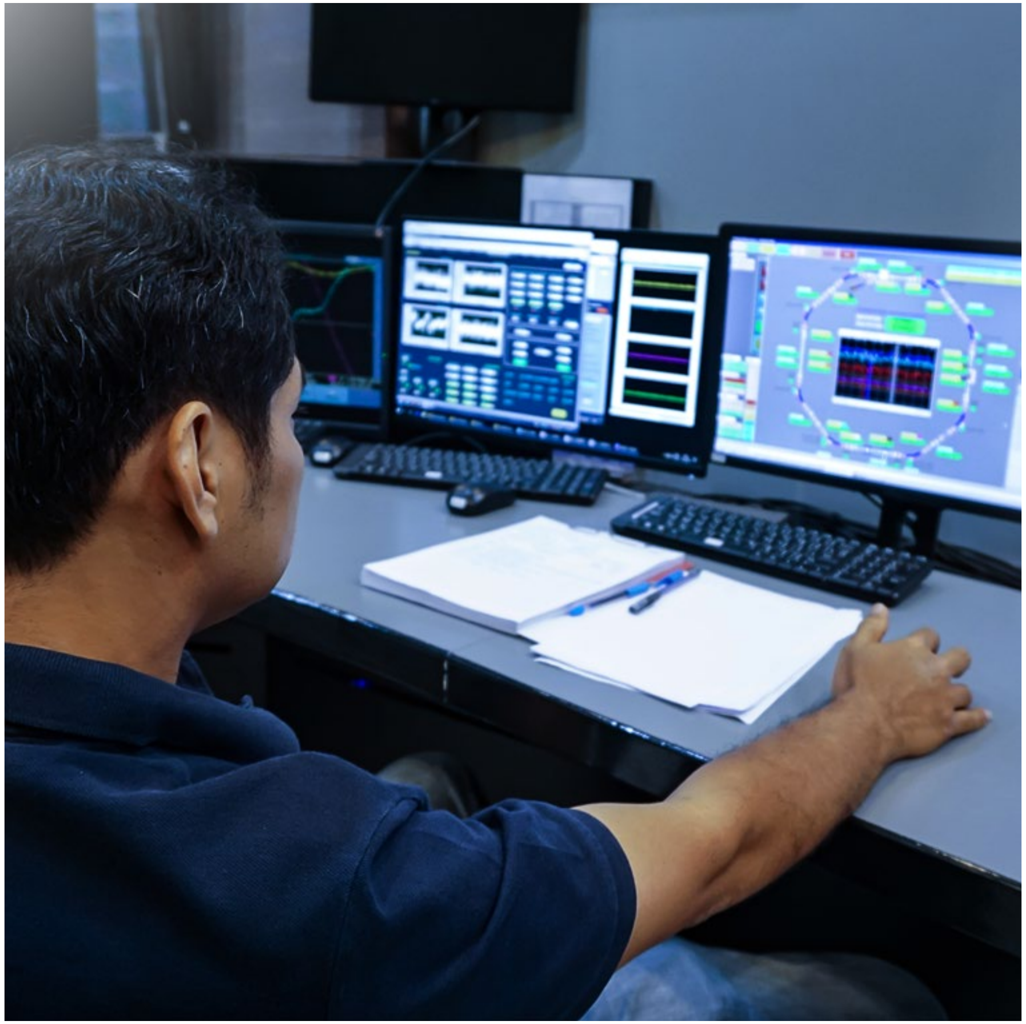
Sophisticated software modelling to estimate fault levels is a mature approach and has been proven to provide an acceptable representation of the network– as long as network owners update the model with accurate input data.

One issue is that installed design load will likely change over time, and the infrastructure will age. “All distributed generation adds complexity to the models – we no longer operate on the traditional spine and network model. You need to know the characteristics of each element and add it to the model to make sure everything’s safe,” says Edwards.

She continues: “The model does not require a specific network configuration, and the techniques can be used on any network and even during network design. But it has to be recalculated often, and maybe not all input values can be found or measured. That means that assumptions are made – and models can quickly become out of date. Or different software can give different values.

“The network is getting more complicated, so it’s harder for models to deal with it. Unless you measure it, you can’t be sure what’s actually happening.

“We see the two techniques being used in combination – fault level measurement gives you a ‘here and now’ figure; modelling allows you to plan for future developments. Real Time Fault Level results can revolutionise active network management, creating the safest network possible while enabling it to grow safely to respond to demand,” summarises Edwards.



> The model has to be recalculated often and not all input values can be found or measured
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RTFLM v PM7000FLM

The portable PM7000 Fault Level Monitor uses natural disturbances to generate measurements, and can achieve a fault level measurement of 2-3% accuracy, depending on the current transformers (CTs) and voltage transformers (VTs) used. Although it cannot provide the benefits of real time visibility, it can show more significant changes in fault level as and when they happen, provided there are enough, relevant disturbances.

The compact device complements existing practices by refining the accuracy of computer-based models. It can validate these models to verify equipment protection settings, or it can provide a value on a section of network not previously modelled. DNOs outside the UK have also used the PM7000FLM alongside their IEEE 519 studies, the international standard that sets limits on voltage and current distortion.

A common misconception is that faults are needed on the network for the PM7000FLM to work. This is not the case. The natural disturbances measured by the unit can be of as little as 0.15% voltage variation in order to generate a result.

The device has been available since 2011, and is now used by all the UK DNOs as well as in the US, South America and the Middle East. In many cases where it has been deployed, the PM7000FLM has indicated that the actual fault level is lower than that predicted by modelling alone. In general, when planning for additional demand load or generation, using the device may allow networks to operate closer to fault levels with confidence, and avoid unnecessary upgrade costs.

However, a couple of points need to be taken into account. First, the PM7000FLM can only be mounted on a radial network or a radial point on an interconnected network, where it can see all the current flowing, rather than directly onto an interconnected network. Second, it's accuracy can be affected by the secondary CTs and VTs used for connection, and two to three weeks of measurement may be required as the process depends on disturbances occurring naturally on the network.

It can now be weighed up against the Real Time Fault Level Monitor (RTFLM), winner of Best Electricity Network Improvement at the UK Energy Innovation Awards 2019, and shortlisted for Technological Innovation of the Year at edie's Sustainability Leaders Awards 2020.

The device exploits the same processing methodology as the PM7000FLM, but uses its own built-in disturbance generator to apply small pulses to the network using a power electronic switching device connected to an inductor set.

> There could be massive savings by companies that are directly linked to fault level
>
> **Ralph Eyre-Walker, SP Energy Networks**

The RTFLM works on radial and interconnected networks, and can be deployed network-wide (at LV to 33kV). The device is rack-mounted in the substation and comes with up to three modules, allowing load to be varied to suit the target voltage and expected fault level. It measures the network's response to its own artificial disturbance: these micro-loads generate a voltage variation from around 0.03% to 0.1% of the normal voltage level, firing for between 5 and 110 milliseconds and up to 10 times per second. The number of pulses can be adjusted, depending on how quickly the results are needed, or to achieve an average result over a longer period.

While the cost of one unit is quoted at around £30,000, Outram Research stresses that this is far lower than the expense of carrying out a network upgrade. "The RTLFM can be used to tell if the network can accommodate extra capacity without the need to upgrade. There could be massive savings by major companies that are directly linked to fault level," says Eyre-Walker at SP Energy Networks.

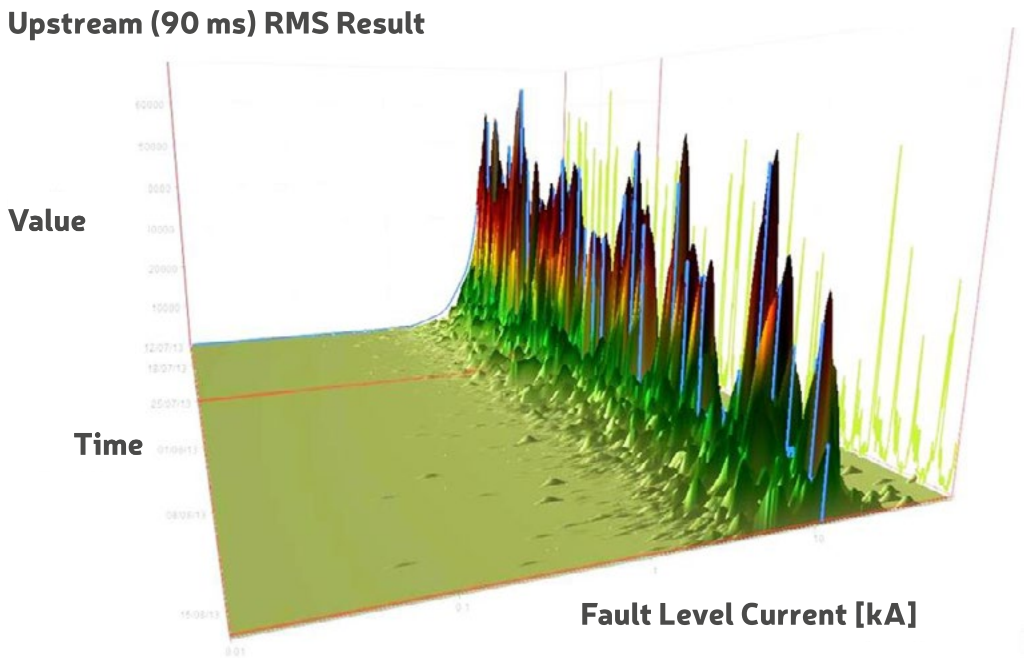
CASE STUDY

Portable PM7000FLM, Chester 2013

SP Energy Networks wanted to improve security of supply for Chester city centre, where the fault level was perceived to be close to capacity. The network was supported by a group of four interconnected 7.5 MVA primary transformers, and a fifth that was permanently on standby, partly out of concerns that connecting it would exceed the network's fault level limit of 250 MVA/13.1 kA.

SP Energy Networks and Outram Research carried out a prospective fault level study to ascertain whether or not it was safe to add the fifth transformer into service when needed. The benefits of additional connection would be that the burden on other local circuits would be shared better, the quality of voltage supply for customers in outlying areas would be increased, and security of supply across the network would improve.

The first part of the project involved validating the computer-modelled values for the four transformer group using the PM7000FLM (*see graph, above right*), to gain confidence in the model and any subsequent modelled predictions. The first set of tests showed a lower result from the PM7000FLM vs the model, with no discernible reason, so the model was rrevisited. With an up-to-date value from the Transmission Operator, the modelled result matched the PM7000FLM much more closely.



With this agreement, SP Energy Networks re-modelled the circuit with the fifth transformer brought online, finding that the newly modelled fault level remained below the 13.1kA limit.

The decision was made that it would be safe to add the fifth transformer to the group, and to proceed alongside further measurement using the PM7000FLM. In the altered five transformer configuration, the measured fault level values were again found to be extremely close to the newly modelled estimates, confirming that supply in Chester could be strengthened without reinforcement costs, representing savings of around £250,000.

CASE STUDY 2

RTFLM Trial, Chester 2019

Two Real Time Fault Level Monitors were installed in SP Energy Networks' Manweb area, one in each of the city centres of Chester and Liverpool. Both of these locations, one at 11kV and the other at 33kV, have the additional challenge of having highly interconnected network infrastructures.

The fault level at Station View, Chester, was measured and compared to well-developed models, achieving results with less than 1.1% difference between the modelled and measured values (*see table, below right*). "This was better than we could have hoped for," says Edwards. "We were able to change the configuration of the network while monitoring, to show that the RTFLMs could measure and validate changes in the fault level at MV in real time, or around ten to 20 seconds of when it actually happened. This is world first technology!"

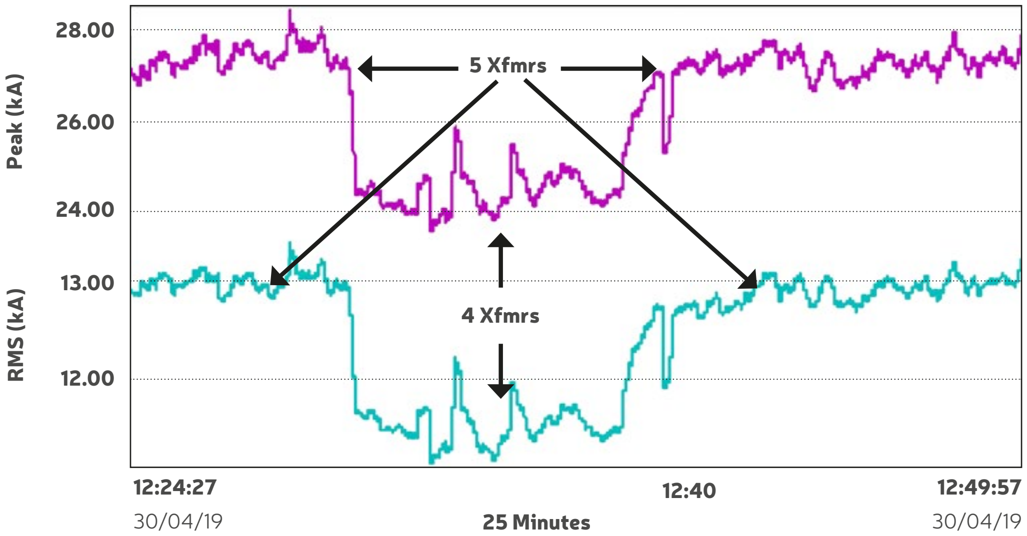
John Outram, Outram Research's managing director, also designed the fault level algorithm. He says: "Comparing the fault level to the voltage after that first recording was very exciting. To see the fault level result follow the voltage, indicating when the network changes were made, in such a short time scale, is revolutionary."

The next stage for SP Energy Networks and Outram Research will be to further trial the artificial disturbance RTFLMs from LV up to 132kV, with the ability to measure the fault level in some cases across two or even three open points in a single substation. The RTFLM would be placed at strategic points on a network, and at greater densities in cities, where the problem of making new connections is particularly acute.

As part of phase two of the project with SP Energy Networks, there will also be collaboration with software specialist, Smarter Grid Solutions, which will incorporate RTFLM values into a wider Active Network Management (ANM) platform, with data integrated into the DNO's SCADA and control room systems. The data will be sent, via a wifi or ethernet connection, to the asset network management software, allowing real-time dashboard views of fault level alongside other operating parameters, such as temperature, voltage or phase angle.

As well as the trials with SP Energy Networks, another UK DNO also hopes to be joining the project, running their own RTFLMs around their network. "We do welcome them on board as it will help progress the project, adding weight to the outcome and that's better for the industry," says Eyre-Walker, adding that he believes that "the other DNOs will be watching carefully".

11kV fault level at Station View, Chester, showing temporary change from five transformers to four



11kV Fault Level at Station View	Modelled	Measured
5 Group Peak Make	27.49kA	27.20kA
5 Group RMS Break	12.92kA	12.89kA
4 Group Peak Make	24.80kA	24.66kA
4 Group RMS Break	11.55kA	11.61kA

> We welcome them on board, as it adds weight to the outcome and is better for the industry
>
> **Ralph Eyre-Walker, SP Energy Networks**

CASE STUDY 3

FLM Pilot, Oman 2019

Outram Research was invited to demonstrate its prospective fault level technology at the Muscat Electricity Distribution Company (MEDC), one of five electrical distribution utilities in the Middle Eastern country of Oman. Three PM7000 Fault Level Monitors were installed on MEDC's network – one each at LV, 11kV, and 33 kV.

The main aims of the project were to give a better understanding of the MEDC system's actual fault levels versus their modelled worst-case values, based on the IEC60909 standard. Secondly, MEDC wanted to ensure safe network operation and understand LV fault level contributions – a significant issue in the Middle East due to high concentrations of residential air-conditioning loads.

It means that our investment strategy is based on real, measured results, not just worst-case modelled results

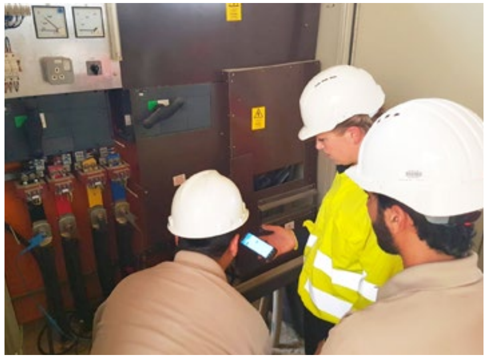
Rimnesh Shah, MEDC

The measurements were undertaken in June and July 2019 as the optimum period, when electricity demand is at peak in line with air-conditioning demand across the network. As expected by MEDC, the results showed that they had more fault level capacity compared to the worst case scenarios suggested by the models.

The trial was initiated by Rimnesh Shah, MEDC planning and GIS manager, after he came across Outram's Fault Level Monitors in his previous role at Northern Powergrid, a UK DNO.

As he explains: "Modelling the values can only go so far, so it was good to do the next level of checks to inform our investment strategy. We found that we had circa 20-30% headroom at different voltage levels to connect more load and new low carbon technologies, before we needed additional investment, for instance in new switchgear.

"The model had suggested that we were close to the limit, but the calculations are based on a worst-case scenarios, in line with best engineering practice around the world. We now have a realistic idea of the LV fault level contribution in the MEDC network, which – along with other countries in the Gulf is quite different from European utilities – to test against the IEC standards as well."



Shah, working with project manager Ahmed Al Busaidi and Sheharyar Khan from the MEDC planning team, have already held dissemination sessions for the rest of the country's distribution utilities where it has been well received with valuable feedback. Going forward, there will be further dissemination to a wider audience.

MEDC is planning to continue to use the monitors for an extended period in the most constrained locations, to further firm up the results of the pilot study and to understand the next level of detail.

As Shah summarises: "The pilot proved that the technology works – we knew that it would, but it had to be proved to the industry here.

"It means that our investment strategy is based on real, measured results, not just worst-case modelled results. And it's brought innovation to the network, because we're not just repeating the same old way of solving problems."

The near-term value case for wider uptake by DNOs

Accurate knowledge of fault levels reduces the risk of assets operating above their design limits, or enables the network to release additional capacity, enabling faster or cheaper connections for customers.

Adding new physical assets is an expensive business. As Ralph Eyre-Walker explains, constructing a new grid substation – and its primary substations – requires an extensive pre-construction spend on acquiring a suitable site and gaining planning permission, before the DNO puts a shovel near the ground or invests in the cabling and equipment.

He adds: "The challenge of creating significant fault level headroom on the network is massive, running into millions of pounds using conventional approaches. Early assessments indicate that innovative solutions such as the RTFLM have the potential to deliver savings of more than £25m in SP Energy Networks' two licence areas alone during the next regulatory review period [RIIO-ED2].

"For example the deployment of a single RTFLM at less than £50,000, along with complementary technologies such as Active Network Management, could defer the replacement of multiple 33kV Ring Main Units at around £500,000 each, and/or 33kV circuit breaker boards at grid supply point (GSP) sites, typically in the region of £2m."

In summary, Edwards says: "It's about not uprating when you don't need to. Alternatively, it's about having increased confidence that reinforcement is absolutely necessary and there really is no alternative, when applying for investment budgets."

In future, a would-be generator seeking a grid connection, or an EV charging company or other business likely to draw a significant load, could be connected with an RTFLM, protecting both them and the DNO. "The industry side might want to connect to the grid, and the DNO has to reject the application on the basis the fault level would peak too high," explains Edwards. "But if an RTFLM was in place, monitoring the fault level and warning that it was about to overshoot the assigned limit, it could trigger a signal to disconnect the customer.

"The DNO could say, 'If you're happy with a flexible connection, monitored using an RTFLM and switched off when the fault level is too high, then we're happy to connect on that basis. The customer could then choose to pay £6m to connect to substation A, or £100,000 to connect to substation B by paying for the installation of an RTFLM. There are options that do not always involve the expense and time of civil works."

Eyre-Walker concurs. "We will install the RTFLM in areas with fault level constraints that we find have some spare connection capacity. The fault level may be lower, most of the time, than the network's operating capacity, but not necessarily all of the time. So if we see the fault level going up [through having an RTFLM], we will have the deals in place to temporarily turn off some customers' supply, or some generation. They can be connected without paying for network reinforcement, but they're the first to lose power in the relatively unlikely event of a fault."

The RTFLM has been called a game changer for the electricity industry. SP Energy Networks and Outram are continuing to work closely, together with industry partners, to give DNOs and other customers the optimum package for their needs.

For further information on this technology, or for more details on the trials, call +44 (0)1243 573050, email sales@outramresearch.co.uk or visit www.outramresearch.co.uk.

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