MEASUREMENT OF EARTH FAULT CURRENT AND EARTH POTENTIAL RISE ON LIVE HV SYSTEMS

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ABSTRACT

Tests were carried out on a live 11kV network to measure the earth-fault level. A pole mounted transformer and LV load were configured to provide a load between phase and earth which could be switched on and off to produce a low level HV fault. The resulting HV current magnitude is below, or for shorter duration than, that which would normally cause earth-fault protection to operate.
The resulting phase-to-earth voltage depression and currents were measured at the load point; analysis yields the overall zero sequence impedance of the system (including soil-return paths) and resulting maximum earth-fault current at that point. This value differs from conventional analysis based on computer modelling which often provides a 'zero-ohm' fault impedance. Consequently measurement provides a real-world figure that can be used more efficiently for design purposes.
It was found that measurement/analysis based on a series of measurements was better than that based on single events.

The earth-potential-rise (EPR) on the transformer tank was also measured relative to a remote earth reference some 200m away. The results were entirely as predicted for a HV earth rod resistance of just under 9Ω. The measurement of EPR is something that is rarely, if ever carried out by network operators in UK, and the results provide additional confidence in the validity of the testing.

INTRODUCTION

The earthing system is a critical safety feature of any high voltage installation and design requirements are well documented [1, 2]. Efficient earthing system design, and safe operation of any system requires accurate knowledge of earth-fault-current (I_F). Typically computer packages are used to calculate I_F but can be inaccurate if unverified/assumed zero sequence circuit impedance data are entered. Furthermore, earth-fault current is influenced by local and remote earth electrode resistance [3], and this information may not be available during modelling. Traditional techniques for measuring earth resistance, such as the fall-of-potential method [4], are subject to error, especially in urban areas where it is not practical to obtain sufficient separation between the earthing network and the current return electrode [5].

The parameter I_F is very significant for safety calculations, since it determines the current that flows during a fault, and can be used to calculate the current flow into an electrode system at or close to the fault-point. Significantly, the ground-return current (I_{GR}), which is proportional to I_F, lifts the potential of the earthing system when it flows to ground through the substation earth resistance (R_B). Thus the ultimate earth-potential rise (EPR) is $I_{GR} \times R_B$. EPR is easily calculated when R_B and I_{GR} are known, but often one or both variables are assumed or calculated and therefore may be subject to error. Given that touch (and step) voltages, to which an individual may be exposed, are directly related to EPR, it is essential that EPR is not underestimated. Often this leads to inefficient assumptions or safety factors being applied which can waste time and money at installation.

The solution to this problem is direct measurement of EPR and / or earth-fault current. Due to the rarity of earth-fault current events, it becomes necessary to apply a 'fault' or phase-to-earth load. To our knowledge, direct application of an earth fault, and measurement of earth-fault level has not been attempted on a customer system in the UK, and would not be permitted on a routine basis. A system has been previously trialed that measures three phase fault level [6] and this work extends this method to phase to earth fault level measurement.

This work is part of wider research being undertaken by UK Power Networks via the Ofgem Network Innovation Allowance into the performance of global earthing systems. It is anticipated that the ability to directly measure earth fault levels on a distribution network may be useful in many cases to allow EPR to be more accurately determined, and consequently will lead to design efficiencies and safety enhancements.

The tests were carried out at the Power Networks Demonstration Centre (PNDC), Cumbernauld, UK. The centre has an 11kV network including overhead lines, cables, transformers, etc., that may be reconfigured to allow experimental testing to be carried out without disruption to any customers.

THE METHODOLOGY

Load was applied phase-to-earth on the 11kV system via a single phase 11kV:250V transformer, i.e. with one HV terminal connected to a phase and the other to earth. In essence, this is the direct application of a low level (high impedance) earth fault. The impedance between phase and earth may be varied by changing the loading on the LV winding of the transformer. Three 2.25Ω resistor banks were used, in varying configurations, connected to the LV winding of a 25kVA single-phase transformer to load the HV network. The HV voltage drop that occurs when a phase-to-earth load (or fault) is applied is related to the impedance of the earth-loop formed by the HV circuit. Thus measurement of voltage drop and load current provides an indication of loop-impedance, which can be used directly to calculate the maximum earth-fault current. The arrangement of the measurement connections is illustrated in Figure 1.

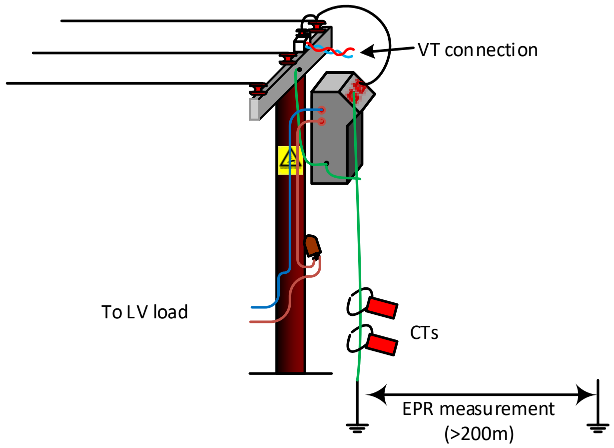

Figure 1. Illustration of the measurement connections.

The resultant current flows and voltage depressions were monitored in different ways to provide a duplicate data set. A combination of fixed monitoring equipment (Beckhoff), and portable units (Fluke storage oscilloscope and Outram PM7000 power quality monitor / Fault Level Monitor [7]) was used as described below. For each test, the 11kV system was energised before LV faults/loads were applied. The LV load steps are described in the Results section below. A total of 11 separate tests were carried out, including the application of a mixture of repeated low-current switching, and shorter duration high current LV faults. The 11kV system was de-energised and made safe after each test, to allow measuring systems to be approached and interrogated where appropriate.

Test Arrangement

For the purposes of this work the PNDC source transformer was used to supply the test transformer at 11kV phase-phase voltage via an overhead line network. The lines include series 'mock impedances' that may be adjusted to simulate the effect of different lengths of overhead line. For this work two different arrangements were used to allow the measurement of two different fault levels.

The earth resistance of the HV electrode at the pole was measured as 9Ω using the fall-of-potential method [4].

Measurement of Earth Fault Current

Connecting the transformer phase-to-earth, as indicated above, effectively allows LV load to translate to a low level HV earth-fault. We chose to measure this current directly in the HV earth download as well as the corresponding LV current. The voltage drop (ΔV) across the 'load' (i.e. the transformer primary winding) was measured at the pole-top voltage transformer (VT), i.e. $\Delta V = V_{no-load} - V_{loaded}$.

A simplified equivalent circuit for the test arrangement is provided in Figure 2.

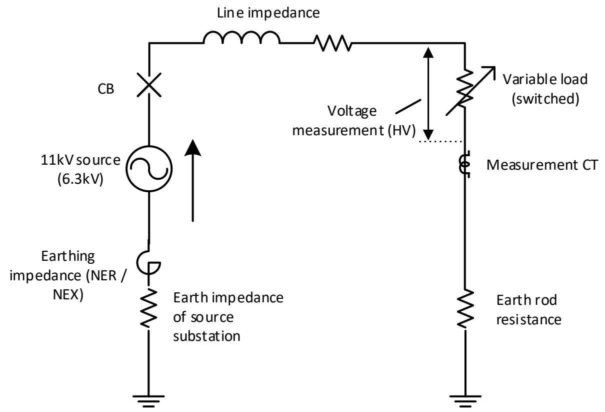

Figure 2. Equivalent circuit for the test arrangement.

The measurement is very similar to that achieved with an electrician's hand-held earth fault loop impedance (EFLI) meter, albeit at 11kV.

The LV load bank resistance (R_{LV}) was varied from 2.25Ω producing the lowest current to a solid (0Ω) connection. For the higher resistance (lower LV current) loads it was possible to switch the load on and off periodically over a 5min duration without protective devices operating. With higher LV currents only one switching event was possible before the fuse or LV circuit breaker operated.

Measurement of Earth Potential Rise (EPR)

In order to measure EPR (voltage rise on the transformer tank with respect to remote earth), a remote, zero volt reference is required. This was achieved by installing a temporary rod electrode beyond the PNDC compound in an adjacent field. In practice a line-of-sight distance of 200m was achieved.

The same temporary electrode was used as the current probe for a fall-of-potential test to measure the earth resistance of the test transformer HV electrode. The resultant curve-shape indicates no significant overlap between the electrode areas; in other words 200m is more than adequate to provide a 'true earth' reference.

RESULTS

The earth fault level was measured for the two different network configurations. The results obtained from the Outram PM7000FLM are subsequently presented. Results were also obtained from the PNDC fixed Beckhoff measurement system and from a portable oscilloscope. These were in reasonable agreement with the FLM measurements especially for the higher current tests. As expected the FLM provided better resolution for lower fault currents as it is able to average a series of successive events which is not as readily available from the other methods. As the purpose of this work was to evaluate the technique, and not a comparison of instrumentation, the results from the other instrumentation is not included for brevity but is available in the full project report.

Earth Fault Current Measurement

The Outram PM7000FLM calculates fault levels dynamically, and can give a live readout for each event that allows a fault level estimate. More detailed analysis is possible using the associated Pronto software [8] that interfaces directly with the instrument. This was found to be quicker and simpler to use than other methods. Two examples of the raw measurement data are provided below. Figure 3 shows the data for Test A from a single load application of high current that resulted in a protection operation. In this case it has been possible to zoom in sufficiently to see the waveforms and the corresponding RMS values are also plotted in real-time.

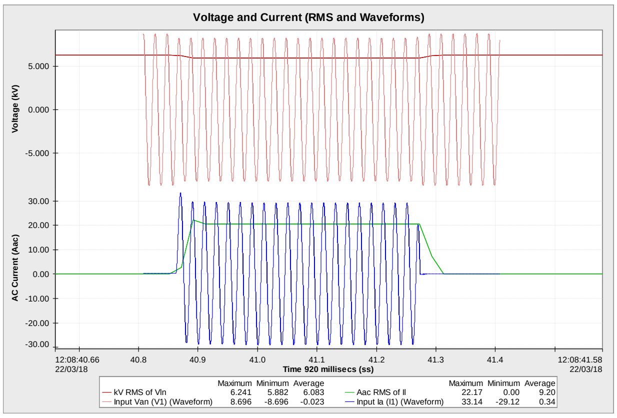

Figure 3. Voltage and current waveforms and RMS results for Test A.

The reduction in HV RMS voltage (ΔV) is evident and the corresponding increase in RMS HV electrode current. Examination of the results indicates a high voltage earth fault level of 375A.

Figure 4 shows similar results for Test B but over a much longer period of time. In this case a series of LV load applications has been made, the first group with a low resistance of 0.75Ω (higher current) and the second group with a 2.25Ω resistance applied. Each depression in RMS voltage, associated with the LV load being switched in, could be used to estimate the loop impedance. However, analysis of all of the individual events allows averaging and provides a more significant result that is more immune to other changes in voltage that may otherwise distort the results.

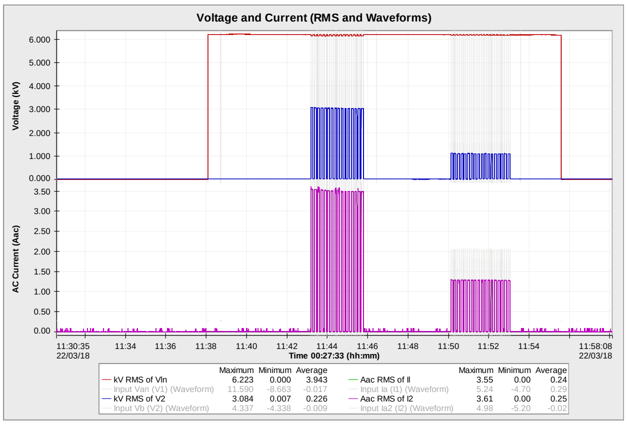

Figure 4. Voltage and current waveforms and RMS results for Test B.

A result of 375A is obtained which is consistent with that from Test A but has been obtained from the application of lower level faults that did not operate protection.

Analysis of the entire data set from Figure 4 can provide an estimate of fault level at a given time, based on a series of monitored events. A cumulative graph for Test B is shown in Figure 5. This does not provide any statistical weighting, moreover it presents a best estimate of fault level at a given moment in time and better assesses the confidence of each event to provide a weighted average fault level instead.

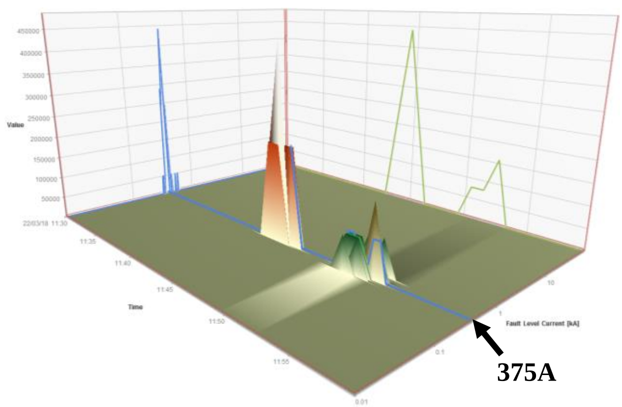

Figure 5. Plot of all significant events with a weighted average fault level as the blue line.

The blue line indicates the significance of each event and, as would be expected, indicates that more weighting should be placed on the measurements with highest fault current compared to those at the lower level of fault current where there is a greater spread in the measured fault current.

Summary of Earth Fault Current Measurements

A summary of the results from 11 different tests is provided in Table 1. The tests include different combinations of LV load resistance and single and multiple load applications. Tests A and B used a different network configuration to the others with a lower overhead line circuit impedance.

Table 1. Summary of results from different test arrangements.

Test	R_{LV}	I_F	Comment
1	2.25Ω	330-350A	Single load switch.
2	2.25Ω	355A	Multiple load switching.
3	1.5Ω	299A	Multiple load switching.
4	0.75Ω	295A	Multiple load switching.
5	0.375Ω	296A	Single switch with fuse operating.
6	0.25Ω	297A	Single load switch with fuse operating.
7	0Ω	297A	Bolted fault, single switch with protection operating.
8	0Ω	302A	Bolted fault, single switch with protection operating. FLM resolution increased.
9	0.75Ω	301A	Multiple load switching with FLM resolution increased.
A	0Ω	375A	Second network configuration. Single load switch with fuse operating.
B	0.75Ω and 2.25Ω	375A	Second network configuration. Multiple load switching. LV load changed during session.

From Table 1 it is evident that the fault level for the initial network configuration (Tests 1-9) is around 300A and rises to 375A for the alternative configuration. Some improvement in accuracy was observed in latter tests as the equipment set up was refined.

Using circuit data provided by PNDC, the calculated values for RMS earth fault level are approximately 265A (network configuration 1), and 302A (network configuration 2). The results from Table 1 suggest a slightly higher fault level; this could be due to non-updated data in the PNDC model, or perhaps due to some of the dominant current-limiting elements (such as mock impedances) performing slightly differently under single phase loading. For example, mutual coupling of ground return currents and line currents could lower the return impedance and increase fault level slightly in practice. This correction is difficult to calculate without accurate geometric data, and unlikely to be practical in real-world assessments.

Other sources of error could be the source transformer earth resistance being less than the 7.47Ω quoted in the site commissioning records. Calculations with the source earth resistance tending to zero in fact produce earth fault levels of 311A and 380A, i.e. in good agreement with the measurement results which might suggest that the PNDC source transformer star point is bonded to a larger electrode system.

Despite these differences, the results achieved during these tests are generally consistent and provide confidence that the method works. There was some variation in measured fault current (when calculated from V and I data), most obviously at low currents where the difference between the longer term, multi-event analysis and any one-off (Ohm's Law) type calculations could be seen.

This difference became less apparent for higher current pulses where the measurement error for single pulses becomes less significant.

Earth Potential Rise Measurement

EPR was directly measured as the voltage between the test transformer HV electrode and the reference electrode located 200m away.

EPR measurement was found to produce a voltage on HV steelwork exactly in phase with downlead current as expected for a predominantly resistive electrode.

Figure 6 shows the EPR measured during the second current pulse of Test 8 for a solid LV fault. A scaling factor of 100 applies in this case (VT ratio), i.e. the peak voltage is around 250V:

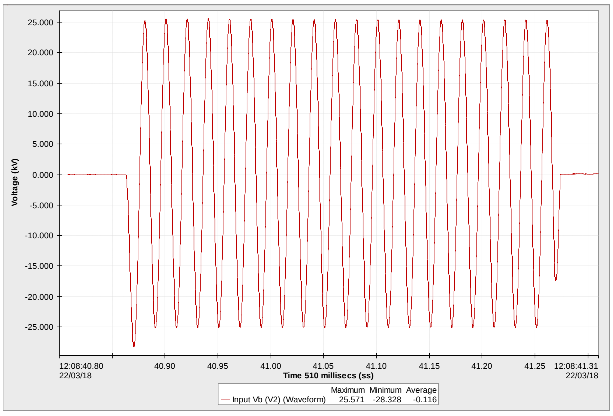

Figure 6. Measured earth potential rise (EPR) for Test A.

For Test A: the RMS voltage = 178V (for 20.52A); this corresponds to an electrode resistance of 178/20.52 = 8.68Ω, i.e. good agreement with the 9Ω measured using the fall-of-potential technique.

Had the reference electrode been further away than 200m from the site, the EPR may have been a few volts higher, giving slightly better correlation, although given the small extent of the electrode system this is unlikely to have made a significant difference in this case.

The inferred resistance of 8.68Ω is most probably more accurate than that determined from the fall-of-potential method, as no assumptions/corrections are required for non-uniform soil models, etc.

It should be noted that the EPR values quoted above are NOT the maximum theoretical EPR, since they relate to a relatively low current (20.52A) rather than full HV earth fault current. The EPR may be calculated as follows:

$$Actual\ EPR = EPR_{measured} \times \frac{Earth{-}Fault\ Current}{HV\ test\ current}$$

Therefore for a 375A fault level,

EPR = 178 x 375/20.52 = 3253V.

This is the same as multiplying 375A by 8.68Ω.

This result is unremarkable but provides confidence in the technique. It is, to our knowledge, the first measurement of EPR on a live distribution system in the UK.

CONCLUSIONS

This trial at PNDC has successfully demonstrated a technique that can measure earth fault current directly from a live system.

Voltage and current data can be collected and analysed in a number of ways, including oscilloscopes, data capture cards, and power quality monitors.

It was found that the Outram PM7000FLM was a simple and effective device to facilitate this data capture. The ability to record a series of voltage change events, and the corresponding change in HV electrode (fault) current allows better averaging and a greater confidence in the final result. This is especially important when the HV electrode currents being measured are low, as would be required if this testing was carried out on a real network without causing the circuit protection to operate or causing a disturbance to customers.

EPR has been measured directly using a remote reference probe and the inferred electrode resistance is in good agreement with that obtained from conventional earth resistance measurement techniques.

FURTHER WORK

It is recommended that this trial be expanded to underground networks, and/or networks with higher fault levels. Given the portability of equipment, it is possible that trials could proceed on a distribution network operator (DNO) network.

In the first instance, we recommend repeating these tests on a DNO's overhead network, before moving to an underground system, as connections to the HV system would be practically relatively straightforward.

In order to apply a moderate fault (i.e. load) between phase-and-earth on an underground system, a safe method of connection needs to be established; most probably this will require a portable transformer and/or load bank which can be connected using separable connectors or similar. There are obvious safety issues to be overcome, but this should not be insurmountable and is worthy of further consideration.

REFERENCES

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[4] IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System, IEEE Std-81, 2012.

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[7] PM7000 Fault Level Monitor, Outram Research Limited, UK.

[8] Pronto for Windows software, Outram Research Limited, UK.