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1. Introduction

1.1. Background
The Flexible Plug and Play (FPP) project was a Second Tier Low Carbon Network Fund (LCNF) project that aimed to enable the connection of Distributed Generation (DG) onto constrained parts of the electricity distribution network without the need for conventional network reinforcement. To achieve this, a number of innovative smart devices and applications were trialled to manage constraints and maximise network utilisation. One of the smart devices trialled was a Novel Protection Relay on which new Protection Schemes were configured in parallel with the existing Directional Overcurrent protection scheme so as to verify their suitability as a replacement.

1.2. Scope
This trial report follows an earlier paper submitted for the IET DPSP 2014, titled “An Investigation into Alternatives to Directional Overcurrent Protection on Grid Transformers to Improve the Network Capacity to Accommodate Reverse Power Flow” in which options for modifying/replacing the existing Directional Overcurrent Protection schemes or settings in the context of enabling greater levels reverse power flow in distribution networks were examined as a precursor to the trial. For clarity, and to provide a single point of reference, this report includes the output of this paper, along with a comprehensive overview of the project trials and subsequent results following the implementation of the trialled solutions.

1.3. Trial location
The area under investigation within the Flexible Plug and Play project is located within Cambridgeshire, UK, and includes two 132/33kV Grid sites, namely Peterborough Central and March Grid. These 132/33kV grid sites support the ten 33kV/11kV primary stations located within the trial area. The area was chosen due to the large amount of existing distributed generation in the area, as well as the high degree of interest in the connection of new generators. The result is the area is now subject to a number of different constraints with increases in connection charges as a result of the need to identify less favourable points of connection or as a result of reinforcement works necessary to accommodate the connection.

1.4. The network constraint
The distribution network in the UK has been designed, with very few exceptions, for the power to flow from the bulk supply point down to the customers, i.e. from the higher voltage to the lower voltage networks. Due to the increased amount of distributed generation connected onto the network, the amount of power generated or requested to be connected has, in a number of cases, exceeded the power required by the demand customers on the network to which it is connected. To avoid restricting the output of generators, or increase the connections charges by moving the point of connection to a higher voltage, it is necessary to explore ways of increasing the level of export power into the upstream networks.

One of the constraints under investigation includes the limiting factors affecting the reverse power flow into the 132kV network, both in this area and the wider network, as a result of the setting of the Directional Overcurrent (DOC) protection on the transformer incomers. This form of protection assumes a certain
direction of “Normal” power flow for its stability and is set to detect and clear faults on the remote end of the higher voltage network. The setting of this protection limits the amount of power allowed to flow upstream through the transformer and, as this setting is often lower than the full plant capacity, it prohibits the full utilisation of the thermal capacity of the network.

This constraint can be illustrated by considering the present response to a 132kV fault. Taking the example at March Grid, for which the network is shown in Figure 1 and applying fault on Circuit 2, the protection systems are designed and set to be sensitive, but equally discriminative, to such a fault. The typical expected sequence of events is shown within the figure and can be summarised as follows:

1. Fault develops on Circuit 2 of the 132kV network.
2. The 132kV protection will detect the fault and trip CB 805.
3. As the fault is still back-fed through the back-energised grid transformers, an intertrip signal is sent.
4. The intertrip signal is received and trips the lower voltage incomer circuit breakers of all of the grid transformers connected to Circuit 2.
5. If the intertrip fails, due to equipment or communication medium failure, the power will continue to flow into the fault through the back energised transformers. The DOC protection schemes on these transformer incomers should have already detected the fault and will now trip their perspective local breakers.
6. If the intertrip and the DOC fail, then the grid transformers lower voltage (LV) IDMT protection might clear the fault. In this scenario, the supplies to the lower voltage busbars will be potentially lost. The LV
IDMT protection will not always detect the fault as it is often not designed to do so and/or it has a current setting which is higher than the maximum load through the transformer. Furthermore, if this form of protection trips, it will give the operator a false impression of the fault type and location, which in turn will result in delaying the system restoration.

For the system to remain stable, the reverse power flow must not exceed the DOC setting, with the levels of generation limited to ensure that the maximum reverse power does not exceed 80% to 85% of the DOC current setting. The firm N-1 capacity at March Grid is 787A and at Peterborough Central it is 1,050A. The original settings of the DOC relays located on the 33kV side of March Grid is 400A and at Peterborough Central is 300A. If the reverse power was limited to between 80% and 85% of the DOC current setting then the maximum allowed reverse power flow of 340A and 255A at March Grid and Peterborough respectively, although it should be noted that the DOC settings for both sites are overly conservative and can be increased without detriment to the protection of the system, This is explained in section 1.5.

A viable alternative to DOC protection, in which the full thermal capacity of the network could be utilised, would benefit both UK Power Networks and their customers

1.5. Directional overcurrent protection overview

In order to find alternatives to DOC protection, it is prudent to understand the design and settings constraints and the role it currently plays in protecting the network. Like all protection systems, DOC protection must:

1. Detect the minimum fault level it is intended to operate for;
2. Be stable to any fault it is not intended to operate for.

The DOC protection scheme under concern is applied following the principles established in ENA TS 41-15 [3]. The DOC relays take their inputs from a set of current transformers (CT) to determine the amount of current flow, and a set of voltage transformers (VT) to determine the direction of power flow. The direction is determined by polarising the line current with the phase to phase voltage of the other two lines (e.g. \( I_a \) is polarised with \( V_{bc} \)) typically via a 90° quadrant connection. The settings of this system are constrained by the following:

1. The DOC protection shall operate for the minimum expected fault level. As the DOC protection typically uses Standard Inverse (SI) IDMT characteristics, the relay current setting shall be selected to pick up for at least half of the minimum expected fault level.
2. The DOC protection shall fully discriminate and operate faster than both the HV Overcurrent and LV Overcurrent & Earth Fault protection on the transformer for up to the expected maximum fault level. To this effect, the DOC settings shall grade with the above mentioned systems by at least 20% on current and 0.3 to 0.4 seconds on response time (depending on type of relays used).
3. The DOC protection will preferably be stable for circulating current between transformers under tap changer run away condition. However, this is not an absolute requirement and will therefore be ignored for the purpose of this document.
4. The DOC protection shall not operate for normal reverse power flow. To ensure stability, and taking into account the error margins within the CTs and relays, the reverse power flow is presently not allowed to exceed 80% to 85% of the DOC current setting.
5. The directionality of the protection is determined by the relay characteristic angle (RCA), or the Maximum Torque Angle (MTA) for mechanical relays which is typically set at 45°.
Recalculating the DOC settings to find the maximum viable settings, instead of using traditional typical settings, has shown that for the two substations the maximum DOC current setting can be increased to:

- 600A for March Grid;
- 640A for Peterborough Central.

This leads to an increase in reverse power flow limit of up to:

- 510A for March Grid (64.80% of firm capacity);
- 544A for Peterborough Central (51.8% of firm capacity).

Figure 2: Vector diagram for the DOC relay response based on the listed constraints.
2. The investigated solutions

This section summarises the solutions that were investigated. It focuses the findings in relation to the 33kV to 132kV system as the reverse power problems are presently faced at this interface level.

For consistency and simplification, all the power flow will be listed in Amps, on a 33kV base, at unity power factor.

2.1. Duplication of Intertipping

From the sequence of events shown in Section 1.4, it can be seen that the DOC will only be called upon to operate in the event of intertrip failure. Therefore, if the intertripping system is securely duplicated, there will be no need for the DOC protection in this application and hence full reverse power capacity can be utilised.

The intertrip scheme can fail if the equipment itself fails or if the communication channels fail. Power supply failure is ignored as this is driven from a DC battery system with N-1 redundancy. For the intertrip scheme has to be duplicated in a way that no single mode failure can disable both schemes. To achieve this secure duplication, additional intertripping equipment will need to be installed and independent communication routes will need to be established.

Where privately owned pilot cables are used, there would normally be a pilot cable associated with each of the circuits. In this case the N-1 one redundancy on the intertrip can be achieved by using spare capacity (if available) on the pilot cable associated with the other circuit. This is illustrated in Figure 3. It can be seen that following a loss of either pilot cables the intertrip scheme will still be functional, although with loss of redundancy, through the other circuit pilot cable.

![Figure 3: Duplication of intertripping using two separate pilot cables](image)

Where the existing intertrip system is reliant on a single radial pilot link the above solution is not be achievable unless additional protection grade communications link are installed or leased. Establishing communication channels purely in response to generator connection tends to expensive and requires significant lead time.

Where a self-healing communication ring is available, the duplicated intertrip scheme will be easily achievable utilising modern multiplexers.
The main advantage of this solution is its simplicity. It is reliant on systems which operatives are already familiar with and its total independence from the amount of reverse power flow. However, it can come at a high cost and will often have long lead times with many external dependencies; hence it is not always a viable solution.

2.2. DOC automatic disable scheme
As most of the 132kV to 33kV transformation sites are typically radial in topography with two interconnected transformers at each site, it can be argued that in an N-1 scenario the intertrip is not actually required. If one transformer is out on maintenance or trips out on fault then a trip on the other circuit of the 132kV system will effectively disconnect the supply to the site whether intertrip is there or not. As intertrip is effectively not needed in such a scenario then the DOC (which is back up to intertrip) is also not needed. To achieve this, the DOC scheme can be disabled when the opposite transformer’s incomer breaker is open. As the DOC is no longer in service during a transformer outage, the reverse power flow limit is now based on the lower of the following quantities:

1. The transformer maximum reverse power thermal capacity;
2. The combined DOC setting of the site as relays will be sharing the reverse power flow during intact running conditions.

However, the above scheme cannot be simply applied to a network which is interconnected on the lower voltage side or where there is a significant amount of synchronous generation which could potentially sustain the load in an islanded mode. This is due to the fact that the 132kV system associated with the site is now no longer the only source of power. If viable from a network power quality, load, security, etc, certain feeders can be tripped automatically under an N-1 scenario. However, this is very network specific and a non-generic solution.

The above scheme is also not suitable for sites with more than two transformers. However, an alternative scheme for such sites would be to have multiple DOC setting groups (requires modern relays) which are automatically selected to suite the running arrangements.

2.3. Directional rate of change of current protection
Instead of looking for the instantaneous values of the current, if a scheme is used to detect the increase in the rate of change of reverse power flow it can be used to detect faults on the HV network. As this method algorithm is not presently commercially available, this solution is not pursued further.

2.4. Directional voltage dependant overcurrent protection
As the system voltage is suppressed under fault conditions, this can be utilised to improve the reach of a current operated relay. Using voltage dependent (or voltage controlled) overcurrent protection, the pickup setting can be increased whilst maintaining the reach setting.

On the networks under investigation, using this method of protection will make the network capable of supporting reverse power flow up to the rating of plant.

However, it is worth noting that for short feeders with a strong fault infeed, the voltage level might not be suppressed enough under a back fed fault to ensure the correct operation of this protection. Also, the studies show that for remote earth faults the voltage might not be suppressed sufficiently to ensure the
required sensitivity whilst maintaining stability. This method could, however, still be used to detect three phase faults if combined with another system to detect earth faults.

2.5. Directional negative phase sequence protection

From sequence component theory, under any unbalance in load or fault there will be a resultant negative and zero sequence components. Therefore, for any faults other than three-phase faults, the fault might be detectable by calculating the resultant negative and zero currents.

Calculations have confirmed that a directional negative phase sequence (DNPS) protection scheme can be used to detect all unbalanced faults. However, what could not be confirmed is the stability of the system. In order for the DNPS scheme to be acceptable, it must be capable of meeting similar criteria to those set in Section 1.4, without which the stability of the scheme, and hence the network it is protecting, might be compromised.

2.6. Transformer side distance protection

As this form of protection is not load related, a distance protection scheme could in principle replace DOC protection. However, the presence of the comparatively large impedance of the transformer works against this scheme.

There are two options:
1. Transformer LV based distance scheme.
2. Transformer HV based distance scheme.

An LV-based scheme will have to reach the remote end of the 132kV line through the transformer. As the transformer impedance is significantly higher than that of the line, the accuracy of the measurement will be severely skewed rendering the discrimination and stability of the scheme unacceptable.

An HV-based scheme will experience very high source impedance to line impedance ratio (System Impedance Ratio – SIR) which again will impact the accuracy of the scheme. Distance protection accuracy in a modern relay is typically ±5% for on-angle fault, ±10% for off-angle faults with a maximum SIR of 30. In the network under investigation, March Grid is found to have a maximum SIR of 28, which is just below the SIR limit for guaranteed accuracy and for others sites has been found to be considerably higher this limit for modern relays. Furthermore, with the transformer “behind” the distance relay, the network topography does not lend itself to give a suitable reach setting that would cover all ends of the teed circuit without grossly overreaching the zones of some of the source side distance schemes.

2.7. DOC with load blinder functions

For a number of years, distance protection relays and schemes have had a load blinder (or load encroachment detection) functions available. This utilised the fact the load and fault angles are significantly different which allows for the necessary discrimination. As illustrated in Figure 4, load blinding is particularly useful in the cases such as of heavily loaded lines or where quadrature characteristics are used for the distance zone reaches. If the current increases and its angle is within the expected the load area, the distance relay will be restrained from operating.
If the above principle is combined with the basic DOC function, the DOC relay will be blind to reverse load but will still operate as normal for normal faults, as illustrated in Figure 5.

This scheme will have the benefit of removing the protection-related constraints on reverse power flow whilst maintaining relatively simple tried and tested philosophy for the protection settings.

The main issue with this scheme is high resistance faults. In such cases, there will be a potential that the fault current angle will be pushed into the blind zone making the relay restrained from operation. This issue can be simply resolved by utilising the voltage depression that occurs under such conditions and disabling the load blinding element in response.
3. The trial

Of the investigated solutions, four schemes were identified as being potentially suitable as a replacement for the Directional Overcurrent scheme, namely:

- Directional Overcurrent (DOC) automatic disabling scheme
- Combined directional negative phase sequence (DNPS) and directional voltage dependant overcurrent (DVDO) scheme
- DOC with load blinder functions
- Duplication of the intertripping

With the exception of the duplicate intertripping scheme, all these schemes have been incorporated into Alstom P142 relays installed on the 33kV side of the transformers, which forms the basis of the FPP trials. The configuration for each of these schemes as well as the expected outputs for each of the schemes has been summarised in the following subsections and include the trial approach and the method. The final Programmable Scheme Logic (PSL) and settings for each of the relays is contained within Appendix 1 to Appendix 4.

3.1. Trial Approach

The trial approach was developed as part of the Trial Design document [4] so as to provide a summary, guide and completeness check for the structured trials, tests and analyses of the modern protection relay trials. This expands on the information provided within the FPP High Level Use Case U02.1 summarised below:

“Various forms of network protection rely on communications between remote locations. Methods such as current differential unit protection, intertripping and carrier-aided distance protection may provide an alternative to the directional over-current protection currently used on the UK Power Networks 33 kV network, which is presenting a barrier to the connection of additional renewable generation. New protection relays will be installed to test the use of the IP-enabled platform in supporting communications-based protection.”

The following subsections provide an overview of this approach to the trials.

3.1.1. DOC automatic disable scheme

The DOC automatic disabling scheme was implemented as part of the replacement of the DOC relays at both March Grid and Peterborough Central.

For Peterborough Central, there are no LV interconnections and the level of synchronise generation supported by the network is such that there are no issues with this scheme.

For March Grid, this was not the case so the automatic disabling scheme also needed to include the auto switching of a 33kV interconnection. This was incorporated as part of the Programmable System Logic (PSL) in the relays installed and has been summarised as follows:
If 1T0 is open, the DOC on GT2 is disabled and the 33kV interconnecting feeder circuit breaker is opened immediately (automatically – no intervention required)

If 2T0 is open, the DOC on GT1 is disabled and the 33kV interconnecting feeder circuit breaker is opened immediately (automatically – no intervention required)

There are no concerns with the stability of this system and, as such, the trial does not include a review of this system. However, it should be noted that there are three secondary substations connected onto the 33V interconnector circuit, all of which are at risk of a single circuit outage in the event that the 33kV interconnecting feeder circuit breaker at March Grid is opened. Additional management procedures have been implemented so as to mitigate this risk, however, because of this, this scheme is not deemed suitable for the long term.

3.1.2. Combined DNPS and DVDO scheme

The relays were configured to provide alarm indications for a combined directional negative phase sequence (DNPS) and directional voltage dependant overcurrent (DVDO) protection scheme. These schemes complement one another, with the primary aim of the DVDO element of the scheme to detect three-phase faults, whilst the DNPS element of the scheme being used to detect unbalanced faults. With the presence of large levels of distributed generation both at the 33kV and the 132kV side of the networks, there is a concern over the level of normal and abnormal negative phase currents and voltage that the scheme might be subjected to for which it must be stable. By configuring the DNPS and DVDO systems to alarm only, the stability of the systems can be verified in a field environment without impacting on the security of the system.

The settings for the combined DNPS and DVDO schemes at both sites were suggested by Alstom as summarised in Table 1.

<table>
<thead>
<tr>
<th>Protection Scheme</th>
<th>Setting</th>
<th>March Grid</th>
<th>Peterborough Central</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNPS</td>
<td>Direction</td>
<td>Forward</td>
<td>Forward</td>
</tr>
<tr>
<td></td>
<td>I2&gt;1</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>DVDO</td>
<td>Direction</td>
<td>Forward</td>
<td>Forward</td>
</tr>
<tr>
<td></td>
<td>V&lt;</td>
<td>24.3</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td>I&gt;5</td>
<td>1200</td>
<td>1800</td>
</tr>
</tbody>
</table>

Table 1: Combined DNPS and DVDO settings for March Grid and Peterborough Central

The schemes have also been configured with 250ms direct time (DT) delay, whilst the DOC scheme has been configured with a SI time delay. This is due to limitations within the relay, which prevent multiple use of the SI time delay. Also, a shorter time was chosen to ensure that appropriate trip signals were generated for any fault conditions, which would otherwise be cleared by the primary protection system. This was deemed necessary to mitigate the reduced likelihood of both a fault occurring on the network, which itself would be considered rare, occurring simultaneously with a failure of the primary protection system against which the system would be graded, which would further reduce the chance of operation.
The aim of the trial was to confirm that the combined system can be used to detect all fault types, whilst providing suitable discrimination for normal system operation and for faults outside of the fault zone. For the DNPS scheme it was also necessary to separately measure the standing negative phase sequence (NPS) levels. The final DNPS scheme settings will then be calculated to ensure they are:

1. 20% higher than the maximum anticipated NPS currents which the DNPS scheme must be stable
2. 50% of the minimum NPS currents which the DNPS scheme must treat as a fault

3.1.3. DOC with load blinder function scheme

The relays were configured to provide alarm indications for two additional DOC schemes. The first of these was a very low DOC setting and without load blinding so as to generate a number of events for non-fault scenarios. The second additional DOC setting will be set at the same low value for the DOC but with the load blinding functionality enabled.

For the load blinder functionality, the settings were calculated in accordance with guidelines provided by Alstom [2]. Of these settings, the only unknown was the load blinder angle, as the other settings can be obtained using known quantities or by utilising existing values from the relays. The lower DOC setting also needed to be determined to ensure that the load blinder could be proven to prevent the operation of the DOC. The trial DOC setting and load blinder angle were determined using data collected from a power quality monitor for which there was approximately six months’ of data available, which is illustrated in Figure 6 and Figure 7 for March Grid and Peterborough Central respectively.

![Figure 6: Real Power vs Power factor at March Grid](image_url)
Based on this data for March Grid, the trial DOC setting was to approximately 220A, at which the worst case power factor recorded was expected to be 0.877. The load blinding angle was set using this power factor with an additional 15° margin applied, the value of which was suggested by Alstom [2].

For Peterborough Central, the levels of power exported onto the 132kV network were not sufficient to trial the load blinder in the forward direction. As such, it was decided to trial the load blinder in the reverse direction. A lower value was used for GT2b to ensure the value was sufficiently to generate the required events.

A summary of the settings required to enable the load blinder functionality for all of the sites is shown in Table 2

<table>
<thead>
<tr>
<th>Protection Scheme</th>
<th>Setting</th>
<th>March Grid GT1 &amp; GT2</th>
<th>Peterborough Central GT1b</th>
<th>Peterborough Central GT2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low DOC with Load Blinder</td>
<td>Direction</td>
<td>Forward</td>
<td>Reverse</td>
<td>Reverse</td>
</tr>
<tr>
<td></td>
<td>Zmin(Primary)</td>
<td>22.71</td>
<td>15.88</td>
<td>15.88</td>
</tr>
<tr>
<td></td>
<td>α</td>
<td>44</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>V&lt;Block</td>
<td>13.2</td>
<td>13.2</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>I2&gt;Block</td>
<td>88</td>
<td>168</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>I&gt;3</td>
<td>224</td>
<td>504</td>
<td>252</td>
</tr>
<tr>
<td>Low DOC</td>
<td>Direction</td>
<td>Forward</td>
<td>Reverse</td>
<td>Reverse</td>
</tr>
<tr>
<td></td>
<td>I&gt;3</td>
<td>224</td>
<td>504</td>
<td>252</td>
</tr>
</tbody>
</table>

Table 2: Load Blinder settings for March Grid T1 and T2
For the trial to be deemed successful, there should be a number of events for $I>3$ but no recorded events for $I>2$, unless the load blinder is off for which there should be both $I>3$ and $I>2$ events.

3.1.4. Duplicate intertrip system
A duplicate intertrip system was also investigated. The communication system for the existing intertrip system will cease to be available from 2018 and, as such, UK Power Networks is replacing these circuits with a private self-healing fibre ring. The works associated with this project, however, have only recently been initiated, with the first stage of the works, which consists of a radial communication network, having been completed in 2014. Unfortunately the complete self-healing ring will not being available until 2017/18. The costs of the system, including the design, supply and installation was approximately £170k. Note that this does not include the costs of the communication system, which would were already covered as part of the project replacing the fibre network.

3.2. Data collected and method of assessment
The data used for the trial has been generated from the following sources:

- Protection relay event records
- Protection relay disturbance records
- Power quality monitors, using the CT and VT inputs used for the protection relays
- Fault studies
- Enmac Alarm Schedules

The following subsections provide an overview of the method used to analyse this data in the context of the trials.

3.2.1. Protection relay event records
As previously mentioned, the relays have been configured to provide alarm indications for each of the trial protection schemes. For clarity, the event type, along with a description for when each of the events should be generated, has been summarised in Table 3.

<table>
<thead>
<tr>
<th>Event</th>
<th>Scheme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I&gt;1$</td>
<td>DOC</td>
<td>This alarm signifies the DOC protection scheme has responded to a “fault”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The alarm is generated when the reverse current exceeds the $I&gt;1$ threshold</td>
</tr>
<tr>
<td>$I&gt;2$</td>
<td>DOC with Load Blinder</td>
<td>This alarm indicates that the DOC with Load Blinder scheme has responded to a “fault”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>These alarms should only be generated within periods when the “Z1 FWD Blinder OFF” condition is true and where the DOC setting has been exceeded for the A, B or C phase.</td>
</tr>
<tr>
<td>Z1 FWD/REV Blinder</td>
<td></td>
<td>The Z1 FWD/REV Blinder alarm will be generated as a result</td>
</tr>
</tbody>
</table>
### 3.2.2. Protection relay disturbance records

The disturbance records include real time measurements of the RMS current and voltage vectors for a period of 1.5 seconds for each event. These disturbance records have been analysed to assess the suitability of the load blinder functionality, with the recorded RMS current and voltage vectors being analysed for I>2, I>3 and Z1 FWD/REV events as follows:

- For I>2 and I>3 events, the quadrature phase-phase voltage was made the reference for the corresponding phase current. The referenced current vector was then compared against the DOC threshold (for I>3) and the DOC threshold with load blinder (for I>2).
- Z1 was compared against the load locus to illustrate whether the load blinding was blocked (switched off) during periods when the Z1 breached.
- I2> was compared against the threshold to illustrate whether to load blinding was blocked (switched off) during periods when the I2 threshold was breached.
- The voltages were compared against threshold to illustrate whether to load blinding was blocked (switched off) during periods when the V< threshold was breached.

The results of this assessment have been discussed in section 3.3, with the complete set of results contained within Appendix 15.

### 3.2.3. Power Quality Monitors

Data was collected from power quality monitors installed on each of the four locations to record a number of parameters at 10 minute intervals, including minimum, maximum and average values. For trial purposes, the main data analysed included:

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I&gt;3</td>
<td>This alarm indicates that the lower DOC threshold has been exceeded</td>
</tr>
<tr>
<td>I2&gt;</td>
<td>DNPS This alarm indicates that the DNPS scheme has responded to a “fault”</td>
</tr>
<tr>
<td>VDep OC</td>
<td>DVDO These alarms will be generated when the voltage falls below the DVDO trial setting</td>
</tr>
<tr>
<td>I&gt;5</td>
<td>This alarm signifies the “DVDO protection scheme has responded to a “fault”</td>
</tr>
<tr>
<td></td>
<td>These alarms will be generated when the VDep OC is ON and the I&gt;5 threshold has been exceeded.</td>
</tr>
</tbody>
</table>

Table 3: Relay events and description

The results of this assessment have been discussed in section 3.3, with the complete set of results contained within Appendix 5 to Appendix 14.
Flexible Plug and Play Low Carbon Networks
Novel Protection Relay – Trial report

- Negative phase sequence currents – maximum recorded values
- Voltage – minimum recorded values
- Current – minimum recorded values
- Power Factor – minimum recorded values

The data collected was compared directly to the scheme thresholds to verify events and to identify any additional events not identified by the relay. The results of this assessment have been discussed in section 3.3, with the complete set of results contained within Appendix 16 to Appendix 19.

3.2.4. Fault studies
Fault studies, undertaken using DigSILENT PowerFactory, have been undertaken to better understand the expected network conditions for a number of different faults and scenarios. The studies were undertaken on one circuit at both sites, as the transformers run in parallel so the results for both would be the same.

The network was first evaluated assuming that the main 132kV protection system had operated but all other Grid substations contributing to the fault, which represents a complete failure of the intertripping system. The network was then evaluated with only the studied site contributing to the fault so as to simulate only the site intertrip failing. For each scenario various difference faults were applied at the remote end of the feeder, with resistive fault impedances from 0 to 100Ω applied in 20Ω intervals for each fault type.

For each fault scenario the following data was recorded
- Voltage magnitude and angle from the 33kV busbar
- Current magnitude and angle from the 33kV side of the transformer on the faulted circuit

This data was compared against the protection relay settings for each of the schemes to confirm that the relays would be suitably sensitive to a range of expected fault conditions. The results of this assessment have been discussed in section 3.3, with the complete set of results contained within Appendix 22 and Appendix 23.

3.2.5. Enmac alarm schedules
All alarms and indications at both of the sites are recorded within the Enmac alarm schedules. These have been extracted and used to confirm the reasons for the events recorded for the combined DNPS and DVDO scheme. The results of this assessment have been discussed in section 3.3, with the complete set of results contained within Appendix 20 and Appendix 21.
3.3. Analysis

3.3.1. Combined DNPS and DVDO Scheme

Analysis of relay events
The events recorded on the P142 relay over the trial period between 16/09/14 to 18/08/14 have been analysed so as to identify all events associated with the combined DNPS and DVDO scheme. The results of this analysis are summarised in Table 4 with a more detailed summary of the events contained within Appendix 5 to Appendix 8.

<table>
<thead>
<tr>
<th>Event</th>
<th>March Grid GT1</th>
<th>March Grid GT2</th>
<th>Peterborough Central GT1b</th>
<th>Peterborough Central GT2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDep OC</td>
<td>11</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>I&gt;5</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I&gt;1&gt;1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4: Summary of DNPS and DVDO events

The three DVDO events, identified from the pickup and or tripping of I>5, and four DNPS events, represented by the I>1 events, recorded at March Grid all occurred during two network disturbances on the 132kV network outside of the protected zone. These were recorded on 08/10/2013 at approximately 09:30 and on 29/10/2013 at approximately 09:00. It will be noted from the event records in Appendix 5 and Appendix 6 that these events were recorded at different times. This difference in time has occurred due to the relays were not being time synchronised as opposed to difference in the actual pickup times of both relays.

For the three instances where I>5 picked up, I>1 also picked up, which suggests that the relays operated as expected. There was, however, a trip event recorded on GT2 for I>1>1 although, as previously stated, the schemes had been configured with 250ms DT delay, which would not be adopted for a backup protection system. As such, it is expected that the relay would have ridden through the fault. This is evident from the fact that, I>1 picked up but did not trip. As previously mentioned, in practice, the time delay for the combined DNPS and DVDO would be similar to that used for the DOC relay, although this was not used as part of the trial so as to ensure suitable operation of the scheme for fault conditions which would have otherwise been cleared by the primary protection system.

The remaining 14 VDep OC events recorded for March GT1 and GT2, which signify that the voltage dipped below the V> threshold for the scheme, all occurred as a result faults on the 33kV network outside of the protection zone. Again, discrimination was achieved as there was no I>5 pickup, as would be expected.

There was a similar DNPS event, recorded at Peterborough Central which coincided with one of the fault seen by the March Grid relays on 29/10/2013 at approximately 09:00. This also occurred as a result of disturbances on the 132kV network outside the zone of protection. In this instance I>5 or I>1 did not pick-up, although the voltage did drop such that a VDep OC event was recorded.

There were no actual faults on the networks during the trial period.
Analysis of results obtained from the fault studies

The results from the fault studies for both sites are have been visualised in Appendix 22 and Appendix 23.

For March Grid, there are two instances where the DVDO scheme would not have operated, both of which were for phase to earth faults with a fault impedance greater than 80Ω. It should be noted that for a number of instances the voltage did not fall below the under-voltage setting, $V_<$, although the fault levels were such that the scheme would have operated, except were previously stated. With the exception of the three phase fault, the DNPS would have caused the scheme to operate in all instances.

For March Grid, the minimum NPS current recorded was 372A, although if the fault impedance is ignored this rises to 1100A. The I2>1 setting of 200A is approximately 54% of the minimum value recorded. To achieve the 50% target, the I2>1 setting would need to be less than 186A.

Similar results were obtained for Peterborough central, although there are five instances for which the DVDO wouldn’t have operated. Again these instances were for phase to earth faults with fault impedances of 60Ω and above. With the exception of the three phase fault, the DNPS would have caused the scheme to operate in all instances.

For Peterborough central, the minimum NPS current recorded was 591A, although if the fault impedance is ignored this rises to 1091A. As with March Grid, the I2>1 setting is slightly higher than the target 50% of minimum NPS current (51%). To achieve 50% the I2>1 setting would need to be reduced to below 295A.

Based on the results from the studies alone, the schemes would have operated for all scenarios considered for both Peterborough Central and March Grid. However, as there were no actual faults on either of the two networks during the trial period, it was not possible to record the actual network conditions during fault, which would have provided some reassurance that the network studies suitably reflect the fault conditions to which the relays would have to be sensitive.

Analysis of the data collected from the power quality monitors

Finally, based on the data collected from the power quality monitors, illustrated in Appendix 16 to Appendix 19, the standing NPS currents on the network for both March Grid GT1 and GT2 were under 15A. The standing NPS currents on the network for both Peterborough central GT2b was similarly under 15A, although for Peterborough Central GT1b this considerably higher at around 110A, which are generated from a transformer that supplies an unbalanced load (railway connection) on the 132kV network.

For both sites, the I2>1 settings, including the reduced settings identified, would well above the 20% margin suggested, suggesting that the DNPS scheme would remain stable for both sites.

3.3.2. DOC with load blinder function scheme

Analysis of relay events and disturbance records

The events recorded on the P142 relay between the trial period 11/07/14 to 18/08/14 have been analysed so as to identify all events associated with the DOC with load blinding scheme. The results of this analysis are summarised in Table 5 with a more detailed summary of the events contained within Appendix 9 to Appendix 12.
Event | March Grid GT1 | March Grid GT2 | Peterborough Central GT1b | Peterborough Central GT2b
--- | --- | --- | --- | ---
I>2 Start | 7 | 1 | 3 | 1015
I>2 Trip | 5 | 0 | 0 | 308
I>3 Start | 244 | 229 | 3 | 852
I>3 Trip | 159 | 193 | 0 | 455
Z1 FWD Blinder On / Off | 13781 | 16130 | 37516 | 356

Table 5: Summary of load blinding events

There are no operations for I>2 where there is not a similar (within 1ms) operation for I>3, and there are no operations of I>2 when the load blinder is on. These results would suggest that the load blinder functionality operates as expected.

For March Grid GT1, disturbance records were extracted for a sample of events, including all events where both I>2 and I>3 have operated and five events where I>3 has operated and I>2 has not. An example of plots of the current phasor for two events are illustrated in Figure 8, Figure 9, Figure 10 and Figure 11.

Figure 8 and Figure 9 illustrate an example where both I>2 and I>3 have operated and it can be seen that the current magnitude and phase angle is within the unrestrained area between the load blinder angle of 44° and the minimum torque angle of 45°. It should be noted that, as this is not a fault, the

Figure 10 and Figure 11 illustrate an example where I>3 has operate and I>2 has been blocked. It can be seen that the current magnitude and phase angle is within the unrestrained area for both I>3 but falls within the restrained area for I>2.

A complete set of plots, including phasor diagrams for I>2 and I>3, Impedance plots, voltage plots and NPS plots for the entire sampled disturbance records are contained within Appendix 15.

Based on the fault studies undertaken the following points for further consideration / discussion:

For March Grid there are three instances where the measured positive sequence impedance fell inside the load portion of the characteristic. These all occurred for a single-phase to earth fault assuming a complete failure of the intertripping system, with a fault impedance of 60Ω and greater. For all three instances the NPS exceeded the I2> threshold, which would have removed the load blinder functionality. The magnitude of the fault currents generated in this scenario exceeded the DOC (I>2) threshold. Based on this, the relay should have operated in these three instances.

For Peterborough Central there are also three instances where the measured positive sequence impedance fell inside the load portion of the characteristic. These all occurred for a single-phase to earth fault assuming a complete failure of the intertripping system, with a fault impedance of 60Ω and greater. For all three instances the NPS exceeded the I2> threshold, which would have removed the load blinder functionality.
The magnitude of the fault currents generated in this scenario exceeded the DOC (I>2) threshold. Based on this, the relay should have operated in these three instances.

The NPS currents recorded for every scenario exceeded the I2> threshold such that the load blinder functionality would have been inhibited.

For the majority of instances, the voltage didn’t go below the under voltage threshold. This aligns with comments in Alstom’s’ guidelines for the application of the load blinder and is due to the large penetration of DG at March Grid.
Figure 8: Current phasor plot for DOC where I>3 has operated

Figure 9: Current phasor plot for load blinding stabilised DOC where I>2 has operated
Figure 10: Current phasor plot for DOC where I>3 has operated

Figure 11: Current phasor plot for load blinding stabilised DOC where I>2 is stabilised
4. Recommendations

4.1. Combined DNPS and DVDO scheme

For the combined DNPS and DVDO scheme, the settings for the DNPS scheme would be taken as 50% of the minimum negative phase sequence and checked to ensure this is greater than 120% of the standing NPS eves. The setting for the DVDO scheme can be taken as 0.7 of the nominal phase-phase voltage.

4.2. DOC with load blinder function scheme

Based on the data collected from the trial, along with the fault studies undertaken, the following approach to can be applied to DOC load blinding schemes being utilised as backup protection for 132kV circuits:

- Overcurrent setting ($I_{>1}$) can be determined using the approach described in section 1.5.
- The minimum load impedance ($Z$ Impedance) can be determined using the following equation:

$$Z \text{ Impedance} = \frac{\text{Rated Primary Voltage} (Ph - Ph)}{\sqrt{3} \times CT \text{ primary rating}}$$

- A load blinder angle ($Z$ angle) of 47° can be used
- The under-voltage setting (Blinding $V<$ Block) can be taken as 0.7 of the nominal voltage
- The NPS setting (Blinding $I_{2}> Block$) can be taken as 0.38 of the CT primary rating
5. Conclusion

The aim of the modern protection relay trial was to assess viable alternatives to DOC protection that would enable the full thermal capacity of the network to be utilised for reverse power, that would have otherwise been prevented due to the limits imposed by the DOC protection settings.

Four schemes were identified as being viable alternatives, namely:
- DOC Automatic Disabling Scheme
- Combined DNPS and DVDO scheme
- DOC with load blinder functionality
- Duplicate intertrip system

Unfortunately both the DOC automatic disabling scheme and Duplicate intertrip scheme have limitations with their application. The DOC automatic disabling scheme would impact on the security of the network if applied to an interconnected network, as the interconnection would also have to be disabled. Also, the DOC automatic disabling scheme can not be applied to sites with more than two transformers. The duplicate intertrip scheme is prohibited by the cost and time associated with the provision of a second communication channel.

As such, the Combined DNPS and DVDO scheme and DOC with load blinder functionality, were trialled as part of the project to assess their suitability and recommended approaches were identified for their application.

With the settings recommended, it was found from the network studies that the protection scheme would remain stable for all instances where the power flow into the 132kV network was caused as a result of load. The system would also respond to all fault types with fault impedances up to 100Ω. Note that 100Ω was the greatest fault impedance considered and not necessarily the greatest fault impedance that could occur. Note, however, for both schemes, there is concern that the standing levels of NPS could affect the stability of the system, which was illustrated by the high NPS currents measured at Peterborough Central. There is also very little data available on the actual levels of NPS that would be generated in various fault conditions.

Following the completion of the trial, the DOC load blinding scheme was implemented at March grid, as this most closely resembled the DOC scheme for which staff have confidence in the operation and testing. At Peterborough Central, the DOC automatic disabling scheme remains.
6. References / Bibliography

1. Al-Riyami et al, 2014. An Investigation into Alternatives to Directional Overcurrent Protection on Grid Transformers to Improve the Network Capacity to Accommodate Reverse Power Flow, DPSP 2014
3. ENA TS 41-15
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