Arc Suppression Coils

Summary

This article outlines how the addition of extensive cable to the 33kV and 11kV networks in Cornwall has affected neutral-earthing design and earth-fault management.

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Note: a glossary and diagram key can be found in the DSOF introduction document on our website

Background

Arc Suppression Coils (ASCs) are the predominant neutral earthing system at 33kV and 11kV in Cornwall. The recent addition of significant amounts of underground cable to these previously overhead-dominated networks (primarily driven by the growth of distributed generation) has introduced new technical challenges in the design, construction and operation of these networks.

Over the last three years, all seven ASC-earthed 33kV networks in Cornwall have had their neutral earthing systems reinforced in response to the addition of cable. Some of these networks are now approaching technical limits that will make it necessary to convert to conventional neutral earthing.

ASCs were first introduced to Cornwall in the 1930s, and are now used to earth most 33kV and 11kV networks in the county. The operation of an ASC-earthed network is best understood by comparison to conventional neutral earthing. Each system is described below.

Conventional Neutral Earthing

In a conventional 11kV or 33kV network, the neutral of each feeding transformer (or its associated earthing transformer) is connected to earth. To reduce earth fault level, this connection is often made through a resistor or reactor of a few ohms. Normal conditions on a conventionally-earthed network are shown in Figure 1.

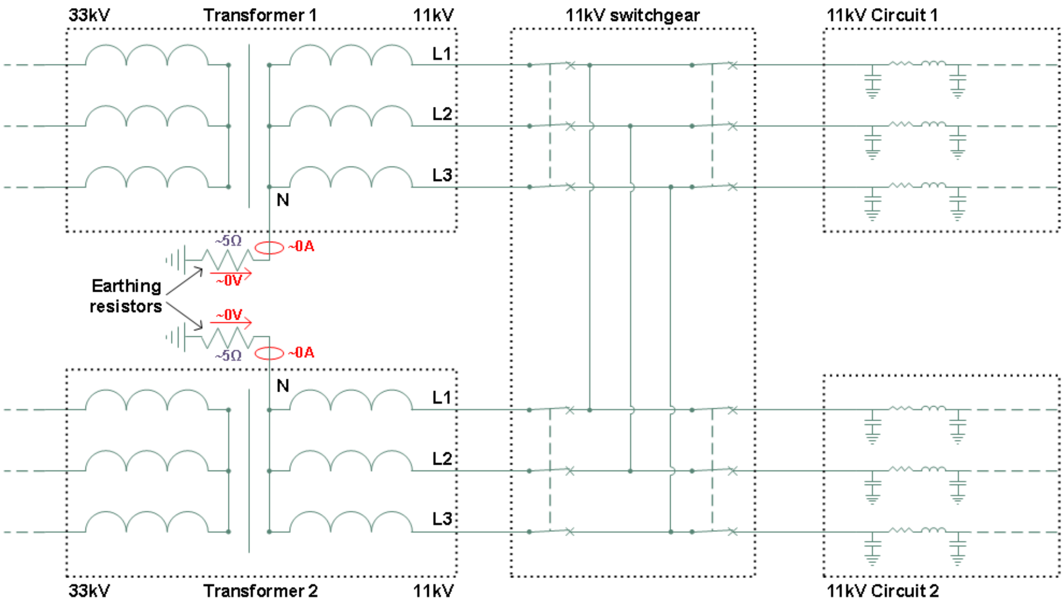

Figure 1: Normal conditions on a conventionally-earthed network (load current omitted)

When a single-phase-to-earth fault occurs on a feeder, fault current flows in the faulted phase of the circuit(s) between the earthed infeed(s) to the network and the fault. A single-phase-to-earth fault on a conventionally-earthed network is shown in Figure 2.

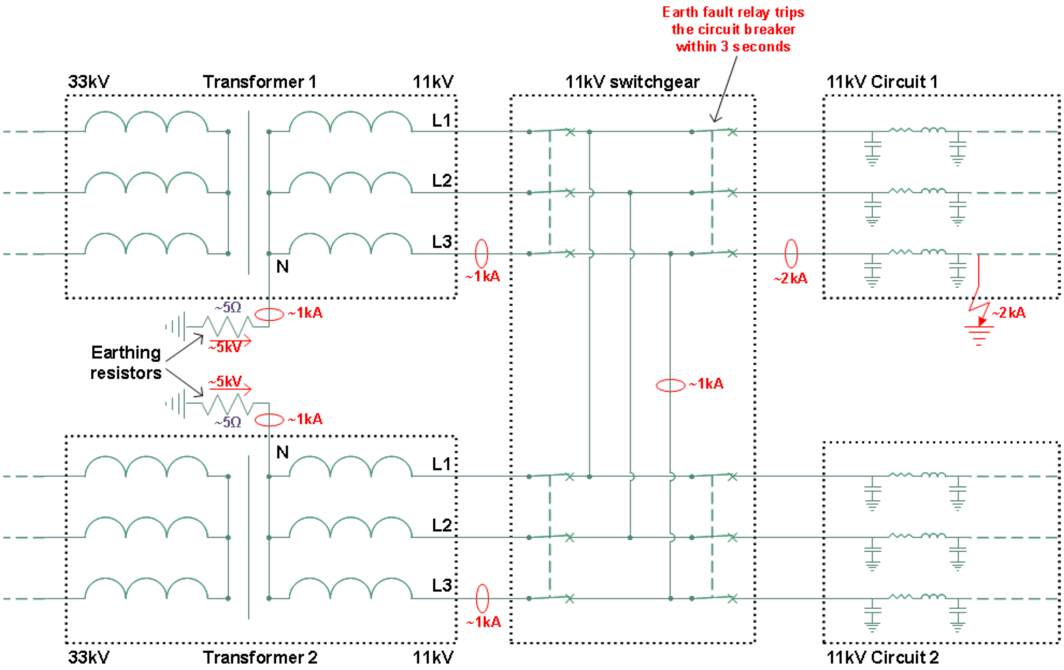

Figure 2: Single-phase-to-earth fault on a conventionally-earthed network (load current omitted)

Current at the Point of Fault

The current at the point of fault is largely determined by the impedance of the network up to the point of fault, and the impedance of the fault itself. Assuming negligible fault impedance, currents of between a few hundred and a few thousand Amps are normal at 11kV or 33kV.

In some circumstances the fault impedance is not negligible, leading to a significant reduction in fault current. High soil resistivity is common in Cornwall. This increases both the earth resistance of the source substation and the resistance at the point of fault, making fault currents of only a few tens of Amps a credible concern.

Current at the Point(s) of Infeed

The sum of the currents at the points of infeed is approximately equal to the current at the point of fault, neglecting charging current and losses. It is shared between the points of infeed according to network impedance.

Fault Detection, Location and De-energisation

When a single-phase-to-earth fault occurs on a feeder, the protection fitted to the circuit breaker supplying that feeder detects the flow of earth fault current and opens the circuit breaker, which de-energises the feeder and so the fault.

When faults occur on overhead networks, they are often transient earth faults caused by contact with trees and other foreign objects. Circuit breakers supplying overhead networks are typically fitted with auto-reclosing equipment. Following fault clearance, the circuit breaker is reclosed, reenergising the feeder. If the fault was transient in nature, the circuit remains energised which minimises interruptions to supplies. If the fault is permanent the circuit breaker trips again, permanently de-energising the feeder. Customers supplied by a single circuit are interrupted by transient faults, but typically only for ten seconds.

ASC Neutral Earthing

When the first 11kV and 33kV networks in Cornwall were developed in the first half of the 20th century, difficulty achieving low enough earth resistance values to ensure protection operation, combined with reduced interruptions from transient earth faults, led to the adoption of ASCs in Cornwall.

Developments in protection equipment later in the 20th century negated many of the benefits of ASCs with regard to high soil resistivity, but not before ASCs became entrenched as the dominant mode of neutral-earthing at 11kV and 33kV in Cornwall.

In an ASC-earthed network, the neutral of each feeding transformer (or its associated earthing transformer) is connected to earth via an ASC. The ASC is an adjustable reactor of between several tens of ohms and several thousand ohms. Under normal running conditions, the ASC is adjusted (commonly referred to as tuned) so that its inductive reactance is approximately equal to (compensates) the capacitive component of the zero-sequence shunt impedance (i.e. capacitance to earth) of the connected network. Accurate tuning is achieved by measuring the voltage across the ASC. When the ASC is in tune, it resonates with the network, resulting in a voltage between a few tens and hundreds of Volts across the ASC. Damping resistors are sometimes used to reduce the steady-state voltage across the ASC. Normal conditions on an ASC-earthed network are shown in Figure 3.

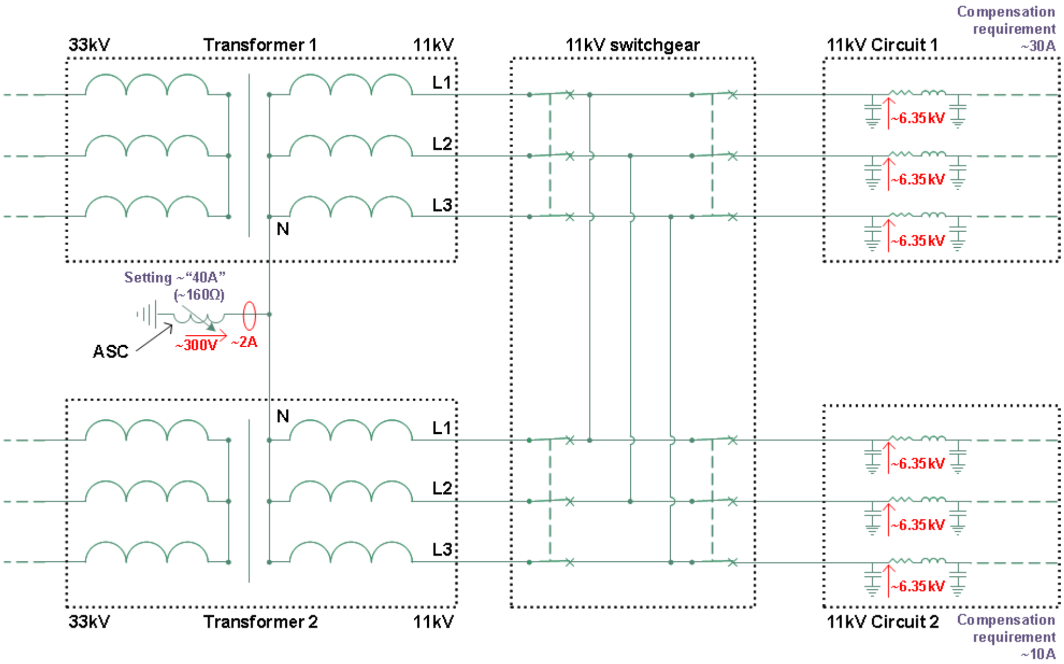

Figure 3: Normal conditions on an ASC-earthed network (load current omitted)

When a single-phase-to-earth fault occurs on a feeder, the voltage across the ASC rises to the normal phase-to-earth voltage of the network. This causes the voltage from each of the two healthy phases to earth to increase to the normal phase-to-phase voltage. The charging (i.e. capacitive) current from the two healthy phases flows into the fault but this is almost entirely compensated by the reactive current from the ASC, resulting in a relatively small current at the point of fault. A single-phase-to-earth fault on an ASC-earthed network is shown in Figure 4.

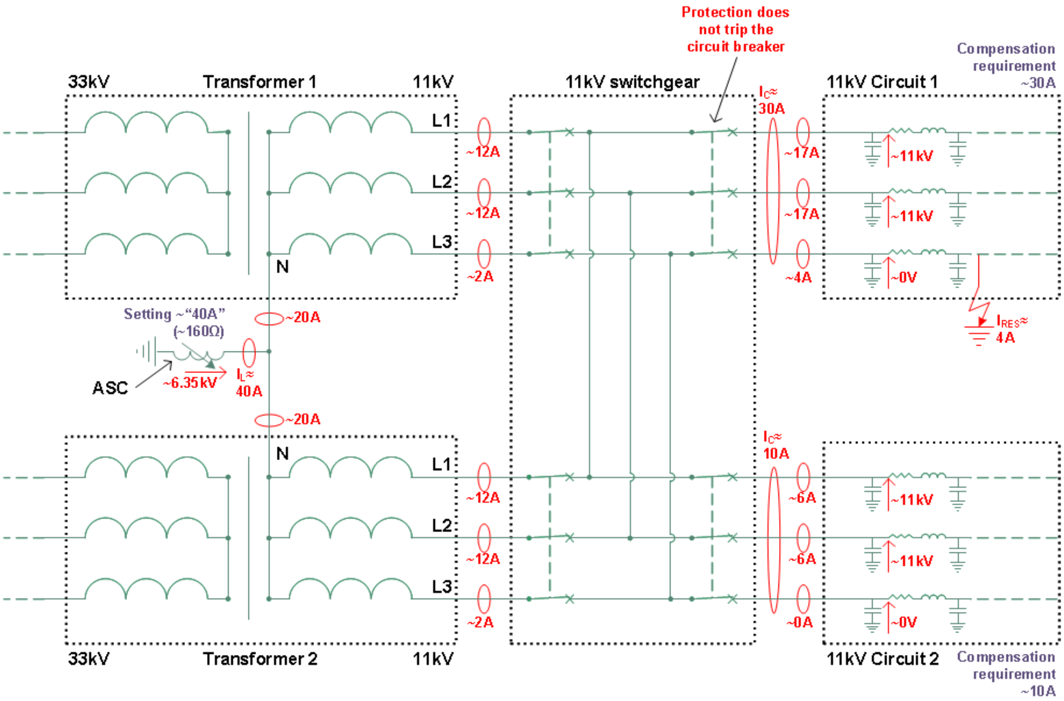

Figure 4: Single-phase-to-earth fault on an ASC-earthed network (load current omitted)

Current at the Point of Fault

Neglecting harmonics, the current at the point of fault (I_{RES}) is the vector sum of:

1. The sum of the charging currents due to the zero-sequence shunt admittance of the circuits in the network ($\sum I_C$), and
2. The total compensation applied to the network ($\sum I_L$).

At 33kV, it is WPD's normal policy to overcompensate the shunt admittance by around 5A. This slight overcompensation reduces the risk of resonant over voltages when circuits are de-energised during fault location.

The exact impact of zero-sequence harmonics and resistive losses is difficult to calculate, but BS EN 50522:2010 [1] allows us to assume that I_{RES} is 10% of I_C where the system is well compensated (i.e. $\sum I_L \approx \sum I_C$). Where the system is not well compensated, the mismatch between $\sum I_C$ and $\sum I_L$ also has to be considered. The magnitude of the current at the point of fault can be estimated as:

$$|I_{RES}| \approx \left|0.1 \times \sum I_C\right| + \left|\sum I_C - \sum I_L\right|$$

Equation 1: Estimation of current at point of fault in ASC-earthed network

This results in a much lower current at the point of fault than in a conventionally-earthed network, but the benefits of the low magnitude of the current must be balanced against the risks of its long duration. Whereas earth faults are normally disconnected within three seconds on a conventionally-earthed network, on an ASC-earthed network they can remain for up to eight hours while the fault is located and alternative supplies to customers are arranged. No customers are interrupted on the inception of the fault; subsequent switching can be arranged to minimise customer interruptions.

Increasing the difference between $\sum I_C$ and $\sum I_L$ during fault location will increase I_{RES} by the same amount.

Current at the Point(s) of Infeed

The current at each point of infeed during a fault is the sum of the compensation applied at that point of infeed. Traditionally this has between a few Amps and a few tens of Amps – many times lower than a conventionally-earthed system. Since the extensive connection of cable, currents in excess of 300A are possible at the ASC-earthed BSPs. Like the current at the point of fault, the benefits of low magnitude must be balanced against the risks of long duration (up to eight hours).

Fault Detection

Faults are detected by measuring the voltage across the ASC. If the voltage exceeds a significant fraction of the system's normal phase-to-earth voltage, a fault is being held on the ASC. If the fault is transient in nature, it will extinguish and the voltage across the ASC will return to normal without any interruption to supplies.

If the fault is sustained for more than a set period (typically ten seconds), an alarm is automatically sent to WPD's network control centre. The ASC damping resistor, if fitted, is automatically switched out to prevent it from overheating. No part of the network is de-energised immediately, and so no supplies are interrupted at this stage.

Fault Location

Because the zero-sequence current flowing in each circuit is due to its own I_C and that of downstream circuits, faults cannot be detected by simple measurement of zero-sequence current. Instead, various methods have been developed to narrow down and finally identify the fault location.

Splitting Networks

If an ASC-earthed network is fed from two substations, it may be practical to temporarily split it into two networks by opening all interconnecting circuits between the infeed substations. The ASC(s) at the substation that is still connected to the fault will still have phase-to-earth Volts across them, while the voltage across ASC(s) at the other substation will return to normal. This allows roughly half of the circuits in the group to be quickly ruled out as not faulty.

It is impractical to accurately match the compensation applied at each infeed substation to the circuits that it would supply if the network were split during fault location. If it is not accurately matched, I_{RES} will increase by approximately the magnitude of the difference between $\sum I_C$ of the subnetwork and $\sum I_L$ of the subnetwork. Together with load-flow considerations, this makes it necessary to recouple the network promptly once the fault location has been narrowed down.

Circuit De-energisation

Each circuit can be de-energised in turn, resulting in one of two outcomes:

1. If it is not the faulty circuit, phase-to-earth Volts will remain across the ASC. While the circuit is de-energised, $\sum I_C$ is reduced by $I_{C\ circuit}$. This increases I_{RES} by approximately $I_{C\ circuit}$, making it necessary to re-energise the circuit promptly before fault location continues.
2. If it is the faulty circuit, the voltage across the ASC will return to normal. The circuit can be re-energised if necessary to restore supplies to customer or enable more detailed fault location using Pathfinder devices.

This method requires the temporary interruption of supplies to customers on some circuits.

Pathfinder Devices

A specialist handheld Pathfinder device is available to assist in the location of earth faults on ASC-earthed systems. It is held under an overhead line in the affected network, and detects characteristic harmonic emissions from the line, which indicate whether or not the Pathfinder is between the fault and the ASC. Following the path of the line with a Pathfinder allows the exact fault location to be found. The Pathfinder is only effective on radial circuits; interconnected circuits must be split by opening circuit breakers to make them radial before the Pathfinder will give unambiguous indication.

While these devices are often very effective, they can sometimes produce erroneous readings. The recent proliferation of switched-mode power supplies in both load and generation equipment has resulted in interference which can limit the effectiveness of Pathfinders.

Fault Direction Relays

Various specialist earth fault relays are available that can indicate the direction towards a fault on an ASC-earthed network. These require accurate current transformers and voltage transformers to detect small changes or abnormalities in voltage, current or power-flow. Various detection methods are used including the detection of transient waveforms, the detection of particular harmonics, and the measurement of the direction of flow of zero-sequence losses.

Temporary Conversion to Conventional Neutral Earthing and Protection

If the affected network is fitted with earth fault protection and all earth electrodes are suitable for conventionally-earthed duty, a suitably rated switch can be closed to short-circuit the ASC and so convert to conventional neutral-earthing. Sensitive earth fault protection is automatically enabled when switching to conventional neutral-earthing. The faulty circuit will then trip as it would in any other conventionally-earthed network.

Fault De-energisation

Once the fault has been located, the faulty circuit is de-energised. If the exact fault location is known and can be guarded to prevent danger, the faulted circuit may remain energised temporarily to maintain supplies to customers.

Network Impact and Detailed Assessment

While ASC-earthing has previously benefited the 11kV and 33kV networks in Cornwall, the changing nature of these networks has introduced several ASC-related challenges to network design and operability.

Neutral-earthing Equipment

ASC Capacity

Sufficient ASC capacity must be available at all times to compensate the connected network. This must cover not just the normally connected network, but also any additional circuits which are transferred into the network under abnormal running. The recent increase in the use of underground cable at 33kV and 11kV has triggered ASC reinforcement at all ASC-earthed BSPs and several primary substations in Cornwall.

Like all plant, ASCs require regular maintenance and are susceptible to faults. This makes it necessary to install multiple independent ASCs so that any one ASC can be switched out of service without adversely affecting the network.

33kV ASC Outages

Until recently, most BSPs had just one ASC. 33kV ASC outages were covered by running the affected BSP in parallel with another BSP with sufficient ASC capacity to compensate for both BSPs' 33kV networks. The growth of distributed generation has made temporary parallels between BSPs less practical, triggering a requirement to install multiple independent ASCs at most BSPs.

11kV ASC Outages

Most primary substations have just one ASC, but have neutral bypass switches and feeder earth fault protection to allow temporary conversion to conventional neutral earthing to cover ASC outages.

ASC Tuning

In order to minimise the current at the point of fault, the ASC must be retuned whenever $\sum I_C$ of the connected network changes. $\sum I_C$ changes primarily due to the connection and disconnection of circuits from the network. Since the capacitance of an overhead line to earth includes whatever is beneath the circuit as the second plate and the air between as dielectric, I_C of an overhead circuit can change in response to weather conditions and the height of crops crowing beneath the line.

Traditionally, ASCs were manually retuned to the connected network both periodically and following significant changes in network topology. With the growth of cable and automatic or remotely-controlled network switching, it has become necessary to retune ASCs more frequently and promptly. Auto-tuning relays are now available that retune the ASC in response to changes in the steady-state voltage across the ASC. All 33kV ASCs are now fitted with auto-tuning relays; 11kV ASCs are being fitted with auto-tuning relays when they are reinforced or replaced.

33kV Earthing Transformer Sustained Neutral Current Ratings

Traditionally, conventional earthing transformers have been used to provide a neutral to connect 33kV ASCs. These are rated for 30 seconds of earth fault current, commonly at 750 or 1050A. Where ratings for 8-hour duty are not available, they are estimated by adiabatic calculations based upon the 30-second ratings. This leads to an estimated rating of 23A for 8 hours on a 750A/30-second unit and 33A for 8 hours on a 1050A/30-second unit. With the addition of cable, these ratings have become insufficient at many sites, triggering reinforcement.

Earthing Systems

Substation Earthing System Sustained Current Ratings

Suitable earth electrodes are often difficult to achieve in Cornwall due to the challenging nature of the ground, which is difficult to excavate and has high resistivity in many areas. The application of ASC-earthing to predominantly overhead networks resulted in much lower maximum earth fault current at both the point of fault and point(s) of infeed than conventional neutral-earthing would have. Historically this may have been used to make economies when building substation earth electrodes.

Source Substation Earth Electrodes

A high-resistance or low-rating earth electrode limits how much ASC capacity can be safely made available at a substation.

The earth electrodes at all ASC-earthed BSPs have recently been assessed for 8-hour duty. Modern practice is to assess new and substantially modified BSP electrodes against the worst case of ASC duty and conventional duty, enabling a future conversion to conventional neutral earthing.

Current at the Point of Fault

If the current at the point of fault (I_{RES}) is too high, there is a risk that transient faults do not self-extinguish or that dangerous touch- and step-potentials are introduced in the vicinity of the fault. Research by E.ON Bayern AG and Siemens AG [2] on 20kV ASC-earthed networks in Germany suggests that I_{RES} of up to 60A may be acceptable, so long as substation earth electrodes are designed to prevent unacceptable touch- and step-voltages.

Whole-network Compensation Limit

At the time of writing, the compensation requirements of different 33kV networks vary from 80A to 320A, leading to a maximum value of I_{RES} of around 37A (Equation 1). WPD now applies a policy that no ASC-earthed 33kV network shall be operated with a compensation requirement exceeding 400A, which should limit I_{RES} to around 45A for an intact network.

As more cable is connected to the network, it will be necessary to split 33kV networks to keep each network's compensation requirement below 400A, or else convert to conventional neutral earthing and protection.

Circuit Compensation Limit

The use of cables several kilometres in length to connect new distributed generation or interconnect urban primary substations has resulted in circuits with compensation requirements of several tens of Amps. WPD now applies a policy that any 33kV circuit which may be deenergised during fault location shall require no more than 25A of compensation.

Where a circuit requires more than 25A of compensation, two solutions are available:

- If the circuit is interconnected (i.e. receives infeed from two or more ends), suitable switchgear can be fitted part-way along the circuit to split it into two or more circuits, each requiring compensation of less than 25A. It is important to note that this solution cannot be applied to radial circuits (those which receive infeed from one end only); or
- Fault-direction relays similar to those used at 11kV can be fitted at each point of infeed to the circuit, removing the need to de-energise the circuit during fault location.

Protection Grading

Although ASC-earthing largely negates the need for earth fault protection relays, some remain necessary. Their settings must be graded against the charging current that they would detect during a held earth fault to ensure that they do not inadvertently trip.

Feeder Earth Fault Protection at Network Boundaries

Circuits on the boundaries between networks are often transferred between those networks in response to faults and other events. There are several 11kV and 33kV circuits which are sometimes supplied from ASC-earthed networks, but supplied from conventionally-earthed networks at other times. These circuits require earth fault protection that will operate correctly in the event of an earth fault while conventionally earthed, but will not inadvertently operate~~d~~ while ASC-earthed.

Neutral Voltage Displacement Protection at Network Boundaries

Radial 33kV circuits, where there is a risk that a fault could be energised through an unearthed transformer winding, are normally fitted with neutral-voltage displacement (NVD) protection. This measures the voltage from each phase to earth; a significant imbalance between these voltages signifies an earth fault and triggers the de-energisation of the circuit. NVD protection cannot be used where faults are to be held on an ASC-earthed network because it would be triggered every time an earth fault is held. NVD protection will need to be retrofitted to all affected circuits.

Radial circuits on the boundaries between ASC-earthed and conventionally-earthed networks require NVD protection which can be remotely enabled and disabled to facilitate prompt circuit transfers without compromising network protection.

Standby Earth Fault Protection

Standby earth fault protection measures the current in the neutral associated with each primary or grid transformer. If excess current is flowing, it trips the transformer. This protects against the failure of neutral equipment including the ASC itself.

The standby earth fault relay cannot tell whether neutral current is due to an earth fault held on the ASC or the failure of neutral equipment, except by the magnitude of the current. The current that flows during an earth fault held on the ASC must be a safe margin below the current setting of the standby earth fault protection. The current that flows in the event of the failure of neutral equipment must be a safe margin above the current setting of the standby earth fault protection. This can be difficult to achieve on networks that use ‘high-impedance’ earthing transformers, since the current that flows in the event of the failure of neutral equipment is relatively small.

Cross-country Faults

During an ASC-held earth fault, the voltage from each of the two healthy phases to earth is equal to the normal phase-to-phase voltage. If an insulating component of the network has a weakness or incipient fault that limits its insulating capability, it may break down when the voltage across it increases. This results in a second fault on the network, on a different phase to the first. Fault current flows into the earth at one fault position, and out at the other. Because the second fault may be remote from the first fault, this condition is known as a cross-country fault.

Depending on the impedance of the two faults, the fault current flowing in a cross-country fault can be very high. If both faults are on the same circuit, it will present to the protection relay(s) on that circuit as a phase-to-phase fault and trip the circuit. If the faults are on two different circuits, one or both circuits may trip depending on their relative protection settings. If only one circuit trips, the fault on the remaining circuit will then become an ASC-held earth fault. If both circuits trip, there is a risk of significant customer interruptions.

To minimise the risk of cross-country faults, WPD uses insulators rated for phase-to-phase voltage on ASC-earthed overhead lines, and requires compatibility with ASC-earthing in specifications for equipment that may be applied to ASC-earthed networks.

Operating larger networks exposes more network components to increased phase-to-earth voltage during ASC-held earth faults, and so increases the risk of a cross-country fault developing. Cable terminations at the transition between overhead and underground sections of network have proven particularly prone to this mode of failure.

Short Term Mitigation and Solutions

Several projects are currently in progress to mitigate the impact of existing and impending issues associated with ASCs.

33kV ASC Reinforcement

Reinforcement works have been completed or are in progress at all ASC-earthed BSPs to increase the ASC capacity. As part of these works, each BSP group has been provided with two or more independently switched ASCs, sized so that sufficient compensation is available for the outage of any one ASC.

All 33kV ASCs are now fitted with auto-tuning relays. These relays can be remotely enabled and disabled, negating the need for some site visits. The feasibility of remotely adjusting ASC tuning is currently being considered.

33kV Earthing Transformer Reinforcement

In order to prevent increased compensation currents from causing the thermal overload of conventional earthing transformers at ASC-earthed BSPs, WPD implemented a policy of strictly limiting how long 33kV earth faults can be held on ASCs. These time limits made fault location more difficult.

Reinforcement works have been completed or are in progress at all ASC-earthed BSPs to replace conventional 33kV earthing transformers with units rated at 400A for 8 hours. These units allow full use of the installed ASC capacity without unnecessarily limiting the time available for fault location. For compatibility with ASC tuning relays and standby earth fault relays, these earthing transformers are low-impedance units.

BSP Earthing Electrode Reinforcement

The assessment of BSP earth electrodes for ASC duty highlighted an impending reinforcement requirement at Rame BSP. A reinforcement project to alleviate this is currently in design.

11kV ASC Reinforcement

In response to the growth of cable, several 11kV ASCs have been replaced by larger units. When manually-tuned ASCs are replaced, the opportunity is often taken to install an auto-tuning relay.

Fault Direction Relaying

To make the location of held earth faults at 11kV faster and less labour intensive, WPD has been trialling fault direction relays fitted to 11kV feeder circuit breakers at primary substations. Following the success of these trials, WPD intends to fit these relays as a standard item on new and replacement 11kV switchboards at ASC-earthed primary substations in future. Fault direction relays are also being trialled at 33kV as part of the reinforcement of Fraddon BSP.

ASC Reinforcement Deferred by Wider Reinforcement

In some cases, the driver for ASC-related reinforcement also drives other types of reinforcement that may defer the ASC-related reinforcement. Fraddon BSP is currently being heavily reinforced in response to the growth of distributed generation. As part of this reinforcement, the Fraddon/Truro 33kV network, which currently requires 320A of compensation, is being split into two separate networks. This will defer the need to convert to conventional neutral earthing and protection to comply with the whole-network compensation limit of 400A.

Long Term Solutions

Most ASC-earthed 33kV networks are now approaching technical limits that cannot be mitigated except by splitting into smaller networks. Where splitting networks is inappropriate, converting to conventional neutral earthing and earth-fault protection will be necessary to enable further network development and expansion. Various types of neutral earthing, earthing and protection equipment will require replacement or upgrading before the networks can be converted. The 33kV network supplied from Hayle BSP in West Cornwall was successfully converted from ASC-earthing to conventional neutral-earthing in the early 1990s.

Neutral Earthing Equipment

WPD's policy on 33kV protection requires that earth fault levels are restricted to 3000A. This allows the economic construction of earth-fault carrying equipment such as earth electrodes and cable screen-wires. To allow multiple transformers to be operated in parallel, the earth fault infeed per transformer is normally restricted to 750A at 33kV.

The 400A/8-hour earthing transformers now used for 33kV ASC duty also have a rating of 1050A for 30 seconds, specified in anticipation of a future conversion to conventional neutral earthing. Because they are low-impedance earthing transformers they will require series resistors or reactors connected in place of the ASCs to reduce their earth fault infeed to 750A per transformer.

Earthing Systems

Since the use of ASCs may have historically allowed economies to be made in building earth electrodes, it is possible that some existing electrodes will not be suitable for conventionally-earthed duty. All affected electrodes will need to be reassessed and, where necessary, reinforced.

Earth Fault Protection

Most 33kV circuits in ASC-earthed networks are operated without earth fault protection. Recently fitted relays have earth fault protection elements which will need new settings to be applied; many older relays will need to be replaced with new relays that are capable of earth fault protection.

Similarly, NVD protection is fitted but disabled at some sites. It will need to be retrofitted at all other affected sites.

It is expected that during the process of converting from ASC-earthing to conventional neutral earthing, some circuits or entire networks will need to be capable of both modes of operation. It may be necessary to fit earth fault protection that can be remotely enabled and disabled to facilitate prompt circuit transfers.

Bibliography

[1] The British Standards Institute, “BS EN 50522:2010: Earthing of power installations exceeding 1kV a.c.,” 2010.

[2] Siemens AG and E.ON Bayern AG, Germany, “Definition Of Criteria To Operate 20 kV Networks With Arc Suppression Coils According To Standards,” CIRED 20th International Conference on Electricity Distribution, vol. Session 3, 2009.