Design & Commissioning of a Distributed IEC 61850 Communication Based Protection Scheme for a Railway Electrification Project

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Abstract

With the electrification of the Great Western route, one of Britain busiest railways, Network Rail will install the new Rationalized Autotransformer System (RATS) at over 50 substations for the first time. The conventional 25-0-25 kV autotransformer electrical traction system will be rationalized by introducing Load Break Switches in place of circuit breakers at the autotransformer sites. To detach faulted traction parts fed by an autotransformer site in a short time, and only having feeder stations being able to interrupt fault currents, a novel protection and restoration scheme was developed. The substations within an electrical section communicate via GOOSE over an extended IEC 61850 station bus to provide sufficient data to automatically isolate the faulted feeders and restore the healthy feeders. A master device per electrical section manages the sequence of events and handles the restoration.

To minimize the risks associated with the introduction of this new scheme, trials were undertaken to test the functionality of the system prior to implementation on operational sites. Therefore three existing substations with a similar infrastructure as the planned substations were taken out of operation at night to serve as a test environment. Based on the topology of the electrical traction system a dynamic network simulation calculated voltage and current signals for the different fault and operation scenarios automatically. The transient signals were then directly applied to a total of 15 distributed relays simultaneously using three GPS synchronized test devices, one in each substation. The whole test system was run by one PC, which made it possible to assess all relay reactions immediately and to alter test cases if needed. This new application-oriented testing approach kept the testing system independent from the complexity of the restoration scheme.

1 Introduction

Network Rail is presently undertaking extensive and significant electrification work, both electrifying routes presently served only by diesel trains and enhancing existing electrification systems to meet the demand of new rolling stock and services. Examples of new electrification schemes are the Great Western route from London to Bristol and South Wales and numerous routes in the North West of England. Enhancements to existing electrified routes include the Crossrail scheme and the forthcoming introduction of Hitachi Super Express trains on the London - Edinburgh East Coast Main Line. This amount of work, combined with the emerging integrated protection and control systems driven by the IEC 61850 standard has led to significant opportunities to improve upon previous methods of providing protection and control.

2 Background on Autotransformer Feeding

For principal routes, Network Rail typically uses autotransformer feeding, where a high capacity supply point is connected to the transmission system, typically at 400 kV, with a transformer providing a 25-0-25 kV supply to the railway. This allows for distribution along the railway at 50 kV, whilst presenting 25 kV to the trains.

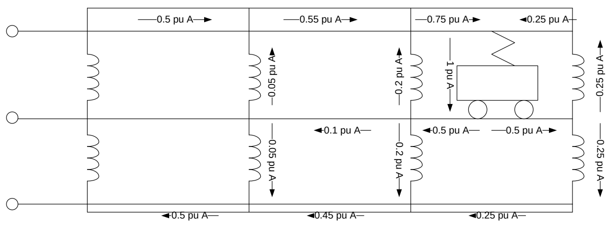

Figure 1: Current Flow in an Autotransformer System

The use of a system such as this typically requires more than twice as much switchgear as a conventional "classic" 25 kV electrification. To reduce this, intermediate Autotransformer Stations (ATS) are tee connected rather than providing full sectioning. Experience on the West Coast Main Line has shown that the tee connected sites give rise to cascade tripping. The tee connected Autotransformers effectively mask the fault from the more remote protection IEDs until the tee connection is removed. This switchgear arrangement increases fault clearance time when compared to classic systems and can result in discrimination problems. Consequently, a limit of one tee connected ATS has been imposed between substations which provide full sectioning. This does not present the optimum solution, as it is both expensive and can only guarantee fault clearance time of 300-400 ms.

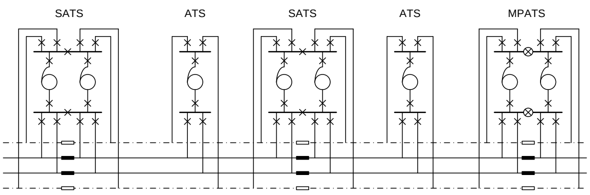

Figure 2: Nominal 40 km Section Conventional Autotransformer System

An alternative scheme, as implemented on high speed lines around Europe is to remove the requirement of the system to discriminate between healthy and faulted equipment, instead de-energizing all feeders, removing all mesh connections, and re-energizing. Any non-transiently faulted sections will trip on re-closing, and subsequently the mesh connections can be re-established to the healthy equipment. New-built lines with large bridges and cut back vegetation produce relatively infrequent faults and therefore the approach above is suitable. The majority of the UK's railway was not initially designed for overhead electrification wiring and thus limited clearance bridges and overhanging trees are frequent. Network Rail policy does not allow automated reclose onto fault. Therefore if multiple Autotransformer sites are required per section, a new solution must be found.

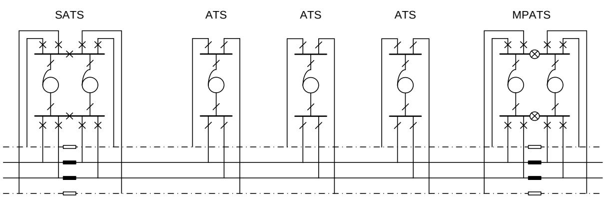

Figure 3: Nominal 40 km Section LGV Autotransformer System

3 Purpose of RATS (Rationalized Autotransformer System)

Historically, substation spacing on Network Rail has been driven by the ability of the protection system to detect and discriminate correctly for faults. This has led to a typical spacing requirement of 10-15 km, regardless of the configuration of the route, with the location of junctions often leading to the provision of additional substations, and the maximum effective protection reach leading to sectioning being provided at locations which provide no benefit to the train service, for example between Stowmarket and Norwich on the Great Eastern Main Line, there is one station and four electrical sectioning points. Similar examples can be found on all 25 kV electrified inter-city routes for which Network Rail is responsible. The provision of so much electrical sectioning is of no tangible benefit to the passenger, whilst increasing the construction and ongoing maintenance costs.

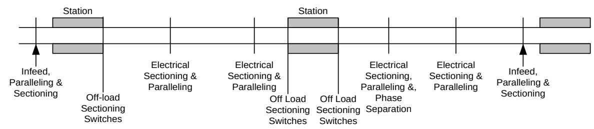

Figure 4: Classically Fed & Sectioned Inter-city Route

It is in this context, along with the significant investment in electrification which the industry is presently enjoying that we asked the question of how to best utilize the emerging IEC 61850 technology, whilst completing the new electrification works as efficiently as possible. The scheme is designed to improve protection performance whilst also reducing the plant requirement, therefore reducing the initial equipment and ongoing maintenance costs. In a rationalized scheme, the plant architecture is similar to that employed on a high speed line, with the primary difference being single pole switching of outgoing circuits, and the necessity of application to long stretches of 4-track railway.

This architecture allows for the money spent on distribution to be concentrated at locations where there is a benefit to the train service, and ultimately to the passenger, with electrical sectioning at stations and junctions.

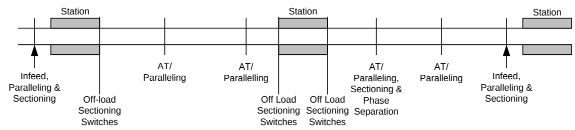

Figure 5: Rationalized Inter-City Route

4 Novel Protection & Automation Scheme

The removal of devices with fault-break capability at intermediate distribution location presents a challenge to the protection, as these devices cannot operate to de-energies a fault. The requirement was to use these, along with the circuit breakers at sectioning sites to provide a protection scheme which will detect and clear primary system faults, whilst not requiring more than one instance of the fault to do so. To reconcile these seemingly contradictory requirements, it was necessary to look at the operation of the high speed line protection scheme. The protection stage is very simple, tripping all outgoing feeds upon detection of any fault. This element of the scheme is used for a rationalized system, with an instantaneous trip issued to all outgoing feeds.

Fault detection is handled by distance protection on incoming feeds and bus sections, where the full fault current is measured, allowing a greater margin between load and fault, than it is possible when fault detection is handled on outgoing feeds. This issues a “Fault Present” signal, which initiates the trip process.

The remainder of the scheme is an automation scheme. In order to prevent having to re-energize the fault, it is necessary to gather information about the fault whilst it is present. Upon receipt of the "Fault Present" message, the IEDs on all feeders take a snapshot of the current directions and any other protection related signals. This occurs during the 60-80 ms that it takes for the circuit breakers to react to the trip signal.

The principle for faults on the overhead line is that every unfaulted line will have at least one reverse current measured, whilst on a faulted feeder no reverse currents will be measured. During the time following the disconnection of all the equipment, the measured current directions are assessed, and the switches on the faulted section or sections are opened.

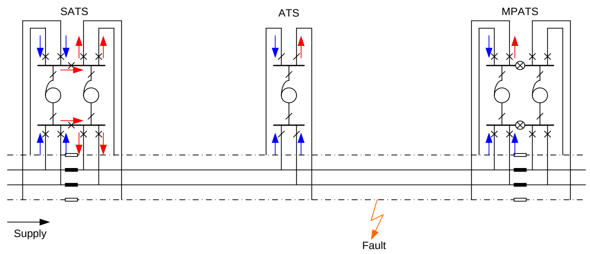

Figure 6: Current Flow Directions during Fault on AT System

Once it is confirmed that all connections to the faulted circuits are open, the circuit breakers feeding the healthy circuits are reclosed, restoring power to the healthy equipment.

Autotransformers and busbar faults are identified using differential protection, which over-rides the indications provided by the current direction. The plant sequence follows the same principles as described for overhead line faults, with the faulted busbar or transformer isolated as part of the automation scheme. Following the isolation of the faulted equipment all healthy overhead lines are re-energized.

The full sequence timing depends on the speed of the load break switches, which typically operate in 5-10 s. For unfaulted feeders this interruption is approximately the same as for running through a neutral section, therefore the disruption to train services will be minimal on healthy lines.

5 Use of IEC 61850

The scheme requires information to be transferred between substations, which can be up to 40 km apart. In order to enable this, GOOSE messaging is employed over an IP network for which a lineside fiber is provided. Parallel Redundancy Protocol (PRP) is used within and between the substations, however as only a single lineside fiber is provided both parallel networks are contained in the same physical medium between substations. Should this fiber fail for any reason, the automation element of the scheme will be inhibited, and following a primary system fault the only action which will be taken is the initial trip of all outgoing feeders.

Whilst it was the introduction of IEC 61850 which acted as a catalyst for the development of this distributed protection scheme, it does not rely on the technology. The same functionality could be provided with other systems, providing rapid communication between substations. IEC 61850 is used because it is an open and interoperable system, not reliant on anyone vendor's proprietary systems.

6 Lessons Learnt from Initial Development

Network Rail invested in a test environment in order to de-risk the transition from a relatively simple system to a connected network which requires tens of devices to work together. This was used to develop the automation scheme logic prior to implementation on operational infrastructure. It additionally enabled development of competency and understanding of IEC 61850 in conventional applications. Initial experiences were documented in the paper "Network Rail and IEC 61850, A User's Perspective of the Standard" presented to the IET DPSP conference in 2012 [2].

During this process it was found that initial IEC 61850 compliant IEDs were not as interoperable as had been advertised. In general the devices themselves were capable of communicating in a satisfactory manner; however the software provided to program them was primarily aimed at setting up communication between devices from a single vendor. Information exchange between vendor tools was difficult and frequently resulted in failure. Workarounds and very specific procedures were necessary and in some cases it was required to manually edit the XML content of the SCL files. This situation has improved since the start of our development program, however, further improvements can, and must be made.

The current state of vendor tools has improved vastly in terms of stability but not by much in terms of usability in a multi-vendor environment. Two IED vendors were in use during the testing. Information exchange between the two IED configurator tools and the system configurator was extremely labor intensive. One of the tools had a very user-unfriendly way of taking information from SCL files which involved reopening the SCL file for each input required from external devices. This seems far away from the intended use of SCL files. This tool, however, was easier to use when modifications to the communication scheme were required.

The initial approach to the RATS automation scheme was to distribute intelligence among the feeder IEDs so that under certain failures some form of automation could continue. A sequence controller was introduced at an early stage to co-ordinate IED actions during fault and non-fault conditions. As the scheme grew to accommodate busbar and AT faults it became apparent that repeating the logic across multiple devices was wasteful. The feeder IEDs had the majority of their logic removed and transferred to the sequence controller. This takes the role of an automation controller and decision maker with the feeder IEDs acting as slaves that provide information.

The RATS automation system requires substantial exchange of binary state information much of which could not be mapped to existing IEC 61850 logical nodes. At the time of testing one of the vendor tools would not accept double point indications also negating the use of XCBR. Therefore GGIO blocks were almost exclusively used. The amount of binary indications required meant that an external database was required. The lack of point naming and description negates one of the benefits of IEC 61850. As the use of GGIO still appears to be commonplace in many installations a new solution to this problem should be adopted. GGIO or something similar should have its internal point names editable. This naming could be conducted in the IED configurator and should thus transfer into the system configurator and into the final IED on the wire output.

7 Field Testing

From the test environment at Network Rail it was a logical step to move forward with a more realistic setup. Due to the large number of relays and the infrastructure components required, in an early stage of the project, Network Rail decided to use three operating substations (with infrastructure similar to the final substations) as a test environment. To avoid any obstruction to the daily rail traffic, the substations were taken out of operation for short periods overnight.

Figure 7: Test Set Wired for Field Testing

The electrical section of the test environment on which the protection scheme was tested, consisted of a feeder station, two autotransformer site, two catenary and two feeder lines. Each line is primarily protected by a single phase, distance protection relay. This already adds up to 12 distance relays, not including the autotransformer differential relays or those on incoming feeders.

The distance relays, bay controllers and sequence controller were all from different manufacturers, making this a truly multi-vendor substation. At the start of every test night, all relays in the system were configured according to the RATS scheme, the test sets were connected to the cabinets and the Sequence Controller was connected to the Ethernet network. Following this, the process of running test cases and adapting the logic scheme (if required) began. To get the substations back in to operation, the whole process was reversed by disconnecting the test sets and returning the relays to their original settings. Overall, the trial tests took almost three weeks to complete.

8 Challenges for Testing

For the trial, it was necessary for all test sets to inject currents and voltages that were time synchronized to all 12 protection IEDs distributed over the three substations. The 'fault present' event of the incoming feeder and the autotransformer fault events were simulated by the test sets as it was not possible to connect these relays during the tests.

Running time synchronized steady-state sequences on each test set, as a well-known and established method, was mainly used during the first half of the trial tests. However in the second half, a new simulation-based testing software was used. This new software was initially developed for three phase power systems and uses a novel testing approach. Running a network simulation, the software automatically calculates the required analogue values for each connected test set. Furthermore, it is also able to control multiple GPS-synchronized test sets from just one PC. To be able to support Network Rail in the trial testing, the simulation software was enhanced to simulate a 25-0-25 kV autotransformer electrical traction system.

The distributed test sets can be controlled either by a direct network connection or via an ordinary Internet connection, for example, via an air card or mobile phone tethering. In the case of an Internet connection, remote access to a test set is granted via a free of charge cloud server infrastructure. For testing the RATS protection scheme, it was possible to configure free ports on the substation network to control the test sets with only one PC. Controlling the tests with only one PC turned out as a great benefit. It did not require any coordination via phone as to when and which test case to start next. Starting the execution was just like using a local test setup. This was very convenient, as it was the first field test for the RATS automation scheme, and the order of the test cases –

even new test cases – had to be created on-site very quickly. In this instance, the test case was created by placing faults and changing breaker states within one minute on the controlling PC, and executing straight away. After every execution, the reactions of, for example, the trip commands of all relays, are transferred to the single controlling software, making immediate assessment of the results possible.

Another aspect of the RATS protection system, which requires special attention, is the communication between the relays distributed over substations and the Sequence Controller. The communication infrastructure at the trial tests was similar to the system which will be installed for electrifications. The usage of a PRP network already makes the protection system highly fail-safe. Nevertheless, we wanted to prove that network latency is not an issue for the system. With two GPS-synchronized network analyzers, we were able to measure the latency of the real traffic between the substations and the redundant network. This was done by time stamping the real GOOSE messages on the network and comparing their timestamps of the exact same messages on each network, and each substation. The network analysis devices were constantly recording the network traffic while the simulation tests were executed. They proved that the propagation delay was as low as expected.

9 Testing Approaches Compared

As during the trial tests steady-state sequence and simulation based testing was used, it was possible to compare the two approaches. While steady-state sequences are a reliable solution, they required much higher effort in terms of preparation and coordination. To prepare a test case, steady-state sequences have to be designed for every relay, including the calculation of the analogue signals for each state at each relay. On the opposite the simulation based approach scales to an unlimited number of relays and all probable test cases and complexities. Initially, it requires some effort to setup the power system model in the simulation based software, but then, every test case simply involves placing faults at various locations in the topology. The simulation ensures that, irrespective of the number of relays, all currents and voltages at all protection relays are consistent, which means that all distances measured by the relays correspond to the same fault, at a single location in the network. This is a must, as the RATS automation scheme decides which switches have to open, based only on the measured impedances and currents. When injecting the impedances derived from the protection scheme, in a worst case scenario, it only tests that the protection system is working accurately for incorrect impedances. Simulating a network with a fault validates that the protection system is safeguarding the network and restoring it as best it can.

10 Conclusion and Outlook

Two phases of onsite testing proved the base logic and highlighted problems that would not have been found during the initial theory stages. These issues were primarily concerned with delays for proper logic evaluation and the use of latched points where fleeting should have been chosen. Onsite testing also highlighted the need for an external database to keep track of GGIO points; Even in the relatively simple single ATS section utilized for testing human error introduced many mismatches.

The next stage for the RATS automation scheme is a more comprehensive bench test, which is being built by the principal contractor as part of the Great Western Route Modernization project, which will cover a larger area than has been possible to test thus far. Following this, the scheme will be implemented as part of final commissioning prior to introduction of electric trains on the Great Western route.

Literature

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About the Authors

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