Simplifying protection system design for distribution substations

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Orion New Zealand (Orion) is a distribution utility that serves the city of Christchurch, the second largest city in New Zealand. Orion is adopting the technical capabilities found in the IEC 61850 standard and other technologies for a simple-to-implement, fit-for-purpose design for distribution protection.

Careful system design allows the use of fewer protective devices, while maintaining the same level of protection system availability and reliability. Wiring and installation concerns are addressed by using process bus communications to provide remote I/O inputs for both analogue measurements and digital control and status inputs, permitting the connection of only one cable to each relay. Benefits of this solution include a standard wiring design for all applications, fewer relay panels, faster installation, and simple expansion by simply connecting relays to process bus I/O units, while meeting performance requirements relating to device lifecycle, design and installation, safety, and commercial business requirements.

Rural substation protection and control upgrade

The company had a project to upgrade the existing electro-mechanical protection at a number of relatively small rural substations. These rural substations are very simple in design, and use metal-clad or metal-enclosed switchgear installed in buildings as the heart of the substation. A typical substation has as a source a 66 kV or 33 kV sub-transmission line, and uses 11 kV as a distribution voltage. The goal was to replace the electro-mechanical protection with microprocessor relays to gain the advantages of convergence of technology, such as metering, SCADA communications, and recording, while simplifying the wiring design and installation. Such a project has several performance requirements beyond the standard requirements of protection and control system reliability and budget limits that any possible solution must meet, including:

A focus on protection system lifecycle: Microprocessor relays have a much shorter lifespan relative to the actual switchgear. Relays are expected to last around 20 years, while switchgear can be reasonably expected to last 40 years or more with proper maintenance. This lifespan introduces a concern about future upgrades and replacement, as the rapid pace of change in microprocessor technology means the relays installed today are unlikely to be available two decades in the future. Therefore, any solution should design from the start a method to support simple replacement of relays in the future.

Design and installation: The typical retrofit project is a custom project, in that all parts of the protection and control system, and the refurbishment/upgrade, is designed for the specific project at the specific substation. Even with the use of standard designs, this potentially leads to a significant design effort for every project.

Relay panels or switchgear doors must be designed for every project, and much of the wiring installation must be done on-site. This also means that a focus on protection system lifecycle is more difficult, as a significant project will be required in the future to upgrade or replace protective relays. Therefore, the goal is to standardise the design as much as possible, and to separate protective relays away from the primary equipment.

Safety: Protective relays mounted directly around primary equipment.

Business pressures: The obvious business pressures are to keep the cost of any project to a minimum, and to keep project costs as predictable as possible for budget planning. Also, there is a strong pressure to maximize the utilisation of technical resources, meaning, in short, to require the least effort and least skills possible to perform the project. A good design for this refurbishment process should also minimize the time and resources needed for future refurbishment, expansion, and upgrade projects. This requires that any new system design and technologies adopted minimise training, learning, and the acquisition of new skills.

Initial protection system design

A protection system design for the small rural substation based on the standard technology in use today will use one protective relay for each zone of protection. To meet the project requirements for lifecycle, safety, design, and cost, the normal path would be to install new microprocessor relays in

![Fig. 1: Initial protection system design.](image)
Placing performance requirements: project requirements. However, the design based on the typical microprocessor relay, installing new doors for the switchgear.

panels, installing the field wiring between cutting out the old wiring, installing the new switchgear to the protection panels, designing the wiring from the protection panels in a separate room means operating personnel do not have to be in the switchgear room during normal procedures. However, high energy signals from CTs and VTs are still present in the relay panels.

Safely: Mounting the protective relays in separate panels means operating personnel do not have to be in the switchgear room during normal procedures. However, high energy signals from CTs and VTs are still present in the relay panels.

Business pressures: Using a standard design, and building the relay panels offsite, significantly reduces the cost, time, and resources required for the project. There are no new concepts, tools, or skills required so the only training is on the new design. There is also no reduction in skills and training required. However, every project is still a custom designed and custom installed project. Furthermore, future projects to address protective relay lifecycle remain a custom engineered project.

The obvious conclusion is that the copper field wiring is the major limiting factor in meeting the project requirements to upgrade the protection system at these small rural substations. Each piece of data used by the protective relays requires a pair of copper wires, which must be designed and installed. As the actual wiring locations and data available are different for each project, each project requires significant engineering effort. An optimal design to meet the project requirements will reduce the impact of field wiring as much as possible.

Beyond that of field wiring, another limiting factor is that the traditional design uses one relay for each zone of protection. Each relay requires significant field wiring to acquire current measurements, voltage measurements, circuit breaker status information, and circuit breaker control points. The amount of field wiring involved is both time consuming, costly to design, and install and also requires a significant amount of panel space to accommodate all the wiring. As a result, a reasonable expectation is that only two feeder relays will be mounted in one control panel. Therefore, the limitation of the technology, the microprocessor relay, limits the methods to improve or simplify the protection and control system design.

Technology to improve the design

There is existing technology that addresses the issues of designing and installing field wiring, and the number of protective relays required for protection. The constraint on using technology is more the perception of the functionality or practicality.

Field wiring, and field wiring design and installation, is directly addressed by the IEC 61850 standard for digital communications in a substation. However, the perception of what the standard is, or should be, limits the practical applications and design choices. The term “IEC 61850” is associated with many concepts, and has negative connotations that include “complicated”, “complete change in design philosophy”, and “communications network based”. This results in the perception that IEC 61850 technology is not ready for widespread adoption, or is too complex to be of value for simple projects such as a protection for a small rural substation. A particular perception is that IEC 61850 requires a significant learning curve in software and communications skills to deliver protection and control solutions.

Multiple zone protective relays that provide up to six zones of independent protection exist today, and are commercially available. However, their use is limited, as the perception is that field wiring is a significant issue. Assuming each feeder requires four currents, three status points, and two control points results in each feeder requiring nine pairs of copper wires. This requires 54 pairs of copper wires for such a relay, a difficult and impractical design. Other perceptions include that operating and maintaining such a relay is more complex procedurally, as isolation for test is more difficult.

IEC 61850 technical concepts

To address this negative perception of IEC 61850, and multi-zone protective relays, it is useful to look at the three powerful technical concepts contained within the IEC 61850 standard. These concepts are self-description of data, peer-to-peer communications of data, and the publishing of sampled value data.
is driven by the needs of the client, and is to have a fit for purpose solution that meets performance requirements. The key is to design a solution, using the concepts within IEC 61850, that is the best solution for the client’s business needs and methods of IEC 61850, that is the complete change in design philosophy, than present day solutions, or require a significant learning curve.

IEC 61850 standard should be. It is important to remember that the IEC 61850 standard itself does not define applications or designs, but simply describes the formats, building blocks, and methods for possible solutions.

Installation in a small rural substation
To really deliver the performance requirements, an intelligent solution designed around the concept of process bus, using the concepts of IEC 61850, seems to be the best solution.

The process interface unit (PIU) is an electronic device intended to be the complete I/O interface of primary equipment for the protection and control system. Essentially, the PIU is a merging unit (that publishes sampled value data) combined with contact I/O for device status and control points. PIUs therefore convert analog signals to digital signals, and publish all data using IEC 61850 message formats over fibre optic cable. The PIU selected for use in rural substations is a simple design, packaged in an environmentally rugged case suitable for outdoor mounting, with connectorised connections for all cables. Each PIU has sufficient I/O (either eight currents, or four currents and four voltages, and contact I/O) to be the I/O interface to two feeders simultaneously, and can establish a point-to-point connection to four different devices independently. The communications uses a specific profile for sampled value data andoose messages compliant with the IEC 61850 standard.

For the purpose of upgrading an old existing electromechanical protection at a number of relatively small rural substations, the company designed the protection and control system using PIUs and multiple zone protective relays. Fig. 2 shows the single line diagram of a 7.5 MVA 33/11 kV substation with 33 kV line breaker, 11 kV incomer and four feeders with the location of the PIUs and the protection functions. The PIUs (which are IP66, NEMA 4X [dust-tight, protected against powerful water jets] and so can be mounted outside) are available in two versions: two sets of three-phase currents or one set of three-phase currents and one set of three-phase voltages. The company chose to use one PIU with two sets of current inputs per pair of feeders, one PIU with the current and voltage inputs on the incomer and one PIU with current and voltage units on the 33 kV breaker.

For economic reasons, the company chose to accept a common mode of failure by sharing one PIU between two feeders. If this is not acceptable, the selected relays allow you to duplicate the PIUs to operate in a redundancy/hot standby mode. The settings allow the redundancy/hot standby operate in security mode (if the two PIUs report discrepancies – block the protection) or dependability mode (if a PIU reports trouble continue using data from the other PIU), or to simply use a single PIU per feeder.

For this design, a multiple feeder relay was chosen for the feeder protection to protect all four feeders (including reclosing), a multiple zone bus differential relay for the bus zone protection which also provides full duplicate feeder backup protection and circuit breaker fail (CBF), and a transformer differential protection relay. This design means that only three IED’s/protection relays (apart from transformer temperature monitoring and voltage control) are needed for the whole substation.

Figs. 3 and 6 show the resulting relay and circuit breaker panels. Note the almost complete lack of wiring in the rear of the relay panels. The only connections to the relays are their power supply, the fibre jumpers to the PIUs and a communication link for SCADA and engineering access. The PIUs are mounted in the the 11 kV switchgear and connect directly to the current transformer, voltage transformer, and control terminal blocks in the switchgear. A single PIU is mounted outdoors on the 33 kV breaker. Local controls use the push buttons on the front of the protection relays and Goose messaging is used to transfer CBF initiate and bus zone undervoltage supervision between relays over the process bus optical fibres.

New design and performance requirements
This new design better meets the performance requirements for the protection and control system design for the small rural substations. Separating the field wiring and I/O from the protective relays makes the system design a component-based design that simply connects together. Each component is an independent piece that can quickly and easily be replaced or upgraded. Specifically:

Protection system lifecycle: Relays are placed in panels separate from the...
Larger substations
The same general design developed for small rural substations can be used in larger distribution substations as well. For these larger substations, the design is simply expanded. One PIU is shared between every two distribution feeders. One multiple zone feeder protection relay connects to two PIUs and protects four feeders. The only difference is in the selection of the specific model of bus protection relay. The bus protection relay provides the same functionality as in the small rural substations design, but this model has the capability to connect to 16 PIUs and provide protection for 24 bus sources and distribution feeders.

Economics
The “business pressures” of the rural distribution upgrade projects is most directly about economics. It is difficult to generalise about costs, however the panel build costs have escalated recently and it is not uncommon for a relay panel with reasonably extensive internal wiring to now cost upwards of R100 000. As an example of costs, each connector block now costs approximately R100 and multi-core secondary cable costs can be over R200 per meter. The use of PIUs and fibre dramatically reduces the amount of both components required along with a significant amount of wiring. Estimates of the cost comparison with a traditional installation in a small substation such as this one relay per feeder, hard wired) are that the costs are very similar. The IEC 61850 Process Interface Units installation may be slightly more expensive; however the added benefits in flexibility may frequently outweigh the initial slightly higher costs. For the illustrated substation, after the design was finalised and under construction, a large dairy factory was built in the area, requiring extensive upgrading of the subtransmission network to meet reliability and quality of supply requirements. The company needed to retrofit three ended 33 kV lines and later upgrade the line to 66 kV. All that was required in terms of installation was to mount a relay in one of the existing panels, connect power and plug in a couple of optical fibre jumpers and it will be operational - a couple of hours installation work followed by commissioning tests.

Other design factors
The system as designed meets the project performance requirements. However, the design, and the tools selected, raises a couple of points of discussion. One is that of interoperability between PIUs of one manufacturer and relays from another manufacturer. The other is related to testing.

Interoperability
The initial response from the industry to this solution was “It is not IEC 61850. It is a proprietary solution. It doesn’t interoperate with equipment from other manufacturers and we can’t interoperate with these PIUs”. IEC 61850-9-2 [1] describes sampled value datasets and part of the reason why IEC 61850 is perceived as complicated is that 9-2 provides massive flexibility in publishing sampled values. To create a practical dataset requires choosing a subset of all available values which meets the needs of a particular application. Currently there are only two published datasets available – the UCA 9-2LE dataset [2] (which is fairly minimal in scope and is available on the UCAIug web site) and the GE HardFibre profile [3] (published in their manuals). Both datasets are fully interoperable as required by IEC 61850 and any manufacturer is free to use them in their relays and their merging units. The conclusion is that interoperability using specific profiles must be specified by end users, and equipment vendors must design products to meet this profile. No doubt there will be more developed in the future. Possibly future instrument transformers may even support multiple datasets and just plug directly in to any relay that has implemented the desired dataset.

Testing
There are two issues related to testing when using this solution. One is the use of PIUs, as the I/O is completely separated from the relays. The other is the use of multiple zone protective relays, and the ability to isolate specific zones of protection for risk-free testing. In this installation, relays are tested by injecting secondary current and voltages directly into the PIUs. This is convenient, as the PIUs are located in close proximity to the relays, even though they are in separate rooms. The switchgear includes test plugs to accommodate this testing.

In transmission substations, where PIUs may be located outdoors hundreds of meters from the relay panels, this method is less practical, and requires the use of substitute PIUs to test relays, and field swapping tested PIUs. When using modem software-driven protection test sets which use a laptop or PC connected to the test set via Ethernet as an HMI, the test technician can simultaneously connect to both the relay and test set using the PC while usually locating himself near the PIU and test set where all the wiring is. The technician can then drive the whole procedure from his PC without having to go near either the relay or PIU. Some technicians like to temporarily install a WiFi base to get connectivity to the relay from out at the circuit breaker/PIU – nice and safe.

Testing multiple zone relays is the more challenging testing issues. The method
previously described of injecting currents and voltages directly into the PIUs is workable during commissioning of the station. During routine testing, however, this is difficult, as multiple relays see the data from the same PIU. In this case, a substitute PIU may be used to test a relay. For example, the multiple zone feeder relay is disconnected from all PIUs or from a specific PIU. The relay is then connected (by patching a fiber at the patch panel) to a substitute PIU wired to a test set, and zones of protection are tested without risk of tripping an in-service feeder. (All contact I/O is now part of the substitute PIU.)

To increase reliability by eliminating common modes of failure, a PIU may be installed for each feeder. To further increase reliability, these PIUs may be shared between feeders, and operated in a redundant fashion. For example, one PIU is connected to CTs from Feeders 111 and 112, and wired to the circuit breakers for these same feeders. A second PIU is also wired to the CTs from Feeders 111 and 112 (in series with the first PIU), and wired to the circuit breakers for these same feeders (in parallel to the first PIU). The multi-feeder protection relay and the bus relay will then use these PIUs in a redundant fashion. One of these redundant PIUs will be the primary PIU for Feeder 111, and the redundant PIU for Feeder 112. The other PIU will be the primary PIU for Feeder 112, and the redundant PIU for Feeder 111. On failure of one PIU, the protection immediately, on a sample-by-sample basis, swaps over to the other PIU, increasing reliability over conventional schemes for the cost of two additional PIUs.

Conclusions
IEC 61850 has evolved into a very sophisticated and complicated standard. The really big question to answer about whether to use IEC61850 is: What problem(s) are you trying to solve with this technology? This example has taken IEC 61850 and designed a solution (which does comply with the standard) to address specific business and engineering problems that face utilities and not just to match an esoteric vision of what IEC 61850 is supposed to be. In the design presented above, this solution solves or mitigates a number of problems that are faced when designing substation control and protection schemes, in terms of lifecycle and lifecycle costs, safety, design and installation, resource utilisation, and economics.

References

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