1. Abstract

Higher capacity substation power transformers (≥ 5MVA), are provided with various protections like differential, overcurrent, earth fault and REF. These transformers could be located 1-4 kms away from the substation due to space restrictions, posing a challenge to the protection engineer, in bringing the associated wirings back to the substation control room. IEC61850 provides a new secondary systems engineering technology to overcome such challenges.

In this paper, I emphasise the use of IEC61850 process bus based solution to meet all the protection requirements of transformers. The sensitivity, selectivity, stability, speed and reliability of the scheme can be achieved, by using a single unit protection relay, with the electrical secondary parameters converted to digital data at the switchyard equipment, and transported through fibre link, with no electrical interference or cable burden issues. It is a neat and clean solution, easy to install and maintain, leading to cost benefit to the user.

2. Introduction

A transformer-feeder comprises a transformer located away from the substation due to space restriction and commercial reasons. There are two main types of transformer feeders:

- Transformer located away from the transmission substation, but present in the distribution substation.
- Transformer located away from both the transmission and distribution substations.

Figure 1 shows an example of transformer feeder, where transformer is located remote to the HV substation.

The physical location of transformer complicates the electrical protection schemes for transformer and associated feeder. The primary requirement is intertripping, since the feeder protection remote from the transformer, will not respond to the low current fault conditions.

**Figure 1** Transformer Feeder
Intertripping is the tripping of the circuit breaker at the other end of the transmission line, for faults in the power transformer. The protective relays at that other end of the line are not sensitive enough to detect turn faults inside the transformer, esp. restricted earth faults. Consequently, the transformer’s own differential-relaying equipment trips the low-voltage breaker and initiates tripping of the breaker at the other end of the line.

Various conventional methods of transformer feeder protection are:

- A line distance protection and a transformer differential protection with intertrip transfer arrangement
- Line overcurrent and earth fault relay, transformer differential relay and the intertrip arrangement
- Pilot wire protection

All the conventional schemes require intertrip arrangement, either through pilot wire or through other communication media. Fibre optic is an option to transfer the signal to remote end.

In this paper, I have suggested use of an IEC61850 process bus based transformer feeder protection scheme. The set up uses GE’s Digital’s hardfibre (Brick) as process interface units (PIUs) at two ends of the circuit, along with GE’s T60 transformer differential relay. The HV and LV end bricks are mounted on respective end switchgears and are connected to the T60 relay through fibre cable. The brick is the interface between the electrical signals (CT/VT and primary operating equipments) and the T60 relay. The secondary cables between the process and the relay are replaced with multimode fibre between the relay and bricks.

The issues in the conventional protection schemes using copper based secondary system are discussed; and the use of IEC61850 process bus fibre optic based solution is analysed.

3. Conventional Transformer Feeder Protection

In the conventional methods, the transformer-feeder can be protected as a single zone or be provided with separate protections for the feeder and the transformer. The transformer is protected by unit protection while feeder could be protected by unit or non unit protection. An alternate is the combination of unit transformer protection with an unrestricted system of feeder protection, plus an intertripping feature.

3.1. Non Unit Protection

The feeder section of transformer-feeder is protected by non unit protection.

3.1.1. Feeder Phase Fault Protection

High-speed protection against phase faults can be provided by distance relays, located at the HV end of the feeder, away from the transformer (Ref Figure 2).
The zone 1 setting of distance relay is set to reach 100% of the line length and could be set well into the transformer impedance. This is due to lumped impedance (transformer impedance) located at the far end of the line. This provides fast fault clearing for the faults in the HV line, but the accuracy on protection reach within the transformer cannot be attained. This is due to the non linear nature of the transformer impedance against distance from neutral. Further, the 100% transformer impedance (definite known impedance) can not be considered as this will interfere with the downstream LV coordination.

The nominal rule is to limit the first zone half way through transformer. The distance protection operation is not affected by varying system conditions.

If the system Thevenin impedance (fault level) is nearly constant, instantaneous overcurrent relays are used rather than distance relays, since the total fault current are readily available through modelling.

The instantaneous protection is usually applied with a time delayed overcurrent element having a lower current setting. In this way, instantaneous protection is provided for the feeder, with the time-delayed element covering faults on the transformer.

When the power can flow in the transformer-feeder in either direction, overcurrent relays will be required at both ends. In the case of parallel transformer-feeders, it is essential that the overcurrent relays on the low voltage side be directional, operating only for fault current fed into the transformer-feeder.
3.1.2. Feeder Earth Fault Protection

The transmission line earth fault relaying, depends on the availability of earth fault source current at the transformer. Instantaneous restricted earth fault protection is normally provided. When the high voltage winding is delta connected, a relay in the residual circuit of the line current transformers, gives earth fault protection, which is fundamentally limited to the feeder and the associated delta-connected transformer winding.

For the HV wye-earthed transformer, HV REF cannot be implemented due to remoteness of transformer. Restricted protection can be applied using a directional earth fault relay. A simple, sensitive and high-speed directional element can be used, but attention must be paid to the transient stability of the element. Alternatively, a directional IDMT relay may be used, with the time multiplier set to low. The slight inverse time delay in operation will ensure that unwanted transient operation is avoided. However, there are sensitivity and the accuracy issues of earth fault component, with this arrangement.

Earth fault protection of the low voltage winding will be provided by a LV restricted earth fault system, using either three or four current transformers, according to whether the winding is delta (with earthing transformer) or star-connected.

3.2. Unit Protection

The differences in requirements of feeder and transformer protections, suggest that the two components of a transformer-feeder, should be protected separately. There is limitation imposed on the transfer of earth fault current by the transformer and there is also a need for transformer protection to be highly sensitive.

This involves mounting current transformers adjacent to, or on, the high voltage terminals of the transformer. Separate current transformers are desirable for the feeder and transformer protections, so that these can be arranged in two separate overlapping zones. Intertripping of the remote circuit breaker from the transformer protection, can be done using the communication facilities of the feeder protection relays.
A unit protection scheme could be adopted by using tapped transformer and differential relays at both ends of the line. This method uses any type of pilot signalling. This scheme is acceptable for phase fault, but has limitations in earth fault protections. The same issue lies with the overall differential scheme.

### 4. Issues with Conventional Schemes

In this section I discuss the issues related to the conventional transformer feeder protection. A case as shown in the Figure 3 is considered for discussion, where separate line differential protection and the transformer differential protection are considered to achieve complete transformer feeder protection.

- To maintain the redundancy in protection schemes for lifecycle, safety, design, and cost, the normal path would be to install relays in separate protection panels, and mount the LV protection panels in a separate room from the switchgear. This is an expensive scheme where the 6.6kV side requires two panels, one for transformer differential and the other for line differential protection.
- Relay panels need to be custom designed to interface with the copper field wiring at HV and LV substations. Any future replacement projects require complete cut out the relay panels and install new relay panels. There will be significant work related to scheme modification, relay and SCADA configurations etc.
- High energy signals from CTs and VTs are present in the relay panels and have safety risks during secondary maintenance works.
- Every project is a custom designed and custom installed project which is significant cost to the business.
- Generally the transmission SCADA monitors the transformer parameters through RTU-relay links. Separate fibre cores need to be provided for transformer data to the control room.
The conclusion is that the copper field wiring is the major limiting factor in meeting the project requirements to upgrade the protection system. 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.

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.

5. IEC61850 Based Process Bus Solution for Transformer Feeder Protection

This section focuses on the application of IEC61850 process bus solution according to IEC 61850-9-2LE using current merging unit (MU) concepts for the transformer feeder protection applications. The process bus solution has technical capability for simple-to-implement, fit-for-purpose design for protection requirement. The concept uses fewer protective devices, while maintaining the high level of protection system availability and reliability. The issues relating to sensitivity in conventional scheme is addressed. Wiring and installation concerns are addressed by using process bus communications to provide remote I/O inputs for both analog measurements and digital control and status inputs, permitting the connection of only one cable each between the merging unit and the relay.

Benefits of this solution include a standard wiring design, 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.

5.1. System Architecture

The process bus solution architecture involves three new tools: the process interface unit, the process bus fibre communication set-up, and the process bus compatible relay.

5.1.1. Process Interface Unit

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. The PIU is designed to become part of primary system equipment, directly connected to current transformers, voltage transformers, and switchgear status and control circuits. PIUs therefore convert analog signals to digital signals, and publish all data using IEC 61850 message formats over fibre optic cable.
The GE Digital’s Brick unit is an example of PIU, which is a simple design, packaged in an environmentally rugged case suitable for outdoor mounting, as in Figure 4. All cable connections to the PIU use industry standard aviation/military style screw-on connectors, to provide simple tools-free installation and removal. Brick also uses a simple, fit-for-purpose, point-to-point communications architecture that doesn’t require network equipment or even an understanding of communications technology.

Figure 4 GE Digital’s Brick

Figure 5 provides the various combination of IO available in Bricks.

<table>
<thead>
<tr>
<th>Brick Variant</th>
<th>AC Currents</th>
<th>AC Volages</th>
<th>RTD TDR Inputs</th>
<th>Contact Inputs</th>
<th>SSR Outputs</th>
<th>Latching Contact</th>
<th>Form C Contacts</th>
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<td>3</td>
<td>18</td>
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</table>

Figure 5 Brick Variants for transformer feeder protection application

In the transformer feeder protection application two Bricks are used. CC-01 type is used at 6.6kV end and CV-01 type is used at 66kV end.

5.1.2. Process Bus Communication

The fibre optic cable that connects to the PIU also contains a pair of copper wires to provide DC power for the PIU. This concept of combined fibre optic / copper cable further simplifies panel wiring design. The 6.6kV PIU gets the DC supply through incomer switchboard DC supply. At 66kV substation end, PIU fibre/DC supply cable is terminated at communication panel where fibres are terminated to patch panel and the DC wires are terminated to the DC distribution board. A multimode fibre cable connects the patch panels between the two substations located at 1-4 km distance.

Two multimode fibre patch cords connect the patch panel to the T60 relays.

Figure 6 is a typical arrangement for fibre patch panel and associated fibre distribution.
5.1.3. Process Bus Compatible Protection Relay

GE Digital’s T60 relay with process bus module is used for transformer feeder protection. For process bus connection it uses the process card which directly connects to the brick through multimode fibre.

With the use of process bus interface card, relay takes direct fibre patch chords from the field. There will not be any CT/VT control cables connected to the relay. The digital inputs/outputs from the site are routed through the bricks. This reduces the control cables in the protection cubicles significantly.

5.2. Protection Overview

The protection overview is shown in figure 8. The PIU at 66kV switchyard collects the three phase current and voltage from CT and VT. It also collects the CB, Disconnector, and earth switch status from respective devices. The 6.6kV PIU collects the 66kV bushing three phase CT inputs, incomer switchboard three phase CT inputs, HV and LV neutral CT inputs and the digital inputs (tap position, CB and earth switch positions).
Each PIU output contacts are configured for trip/close of circuit breakers and the operation of operating devices.

Figure 8 Typical protection overview based on process bus

The T60 relay protection setting is almost similar to the conventional type, except an additional remote resource configuration tool to allow configuration of Bricks.

The configuration process for remote resources is straightforward and consists of the following steps.

- Configure the field units. This establishes the point-to-point connection between a specific port on the relay process bus module, and a specific digital core on a specific Brick. This is a necessary first step in configuring a process bus relay.
- Configure the AC banks. This sets the primary and secondary quantities and connections for currents and voltages. AC bank configuration also provides a provision for redundant measurements for currents and voltages, a powerful reliability improvement possible with process bus.
- Configure signal sources. This functionality of the T60 has not changed other than the requirement to use currents and voltages established by AC bank configuration under the remote resources menu.
- Configure field contact inputs, field contact outputs, RTDs, and transducers. These inputs and outputs are the physical interface to
circuit breakers, transformers, and other equipment. They replace the traditional contact inputs and outputs located at the relay to virtually eliminate copper wiring.

- Configure shared inputs and outputs as required for the application's functionality. Shared inputs and outputs are distinct binary channels that provide high-speed protection quality signalling between relays through a Brick.

The T60 is configured for following protection:

- Transformer Differential (Including cable)
- HV Restricted Earth Fault
- LV Restricted Earth Fault
- HV OC/EF
- LV OC/EF

The current inputs required for HV REF protection is sourced through HV bushing CTs and the HV neutral bushing CTs of the transformer. Hence this protection is more sensitive compared to the conventional protection schemes.

5.3. SCADA application

The T60 relay is mounted in the 66kV substation protection panel (remote to the transformer). This gives an added advantage for SCADA monitoring and control. The real time information available from both ends (HV and LV) of the transformers are acquired in T60 and made available to SCADA through serial or IP based connection to the Master station. The T60 – SCADA connectivity could be through any of DNP3 serial/IP, IEC60870 or IEC61850 station bus arrangement.

In case, there are more output contacts required than the limitation on bricks, additional bricks could be used viz. One Brick each on HV, LV and transformer control cubicles. T60 could be selected with additional output modules.

5.4. Testing

Testing of the whole scheme is carried using modern technology as bricks are located remote to the relay. When using modern 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 one end 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.
5.5. Installation

Following figures show some of the typical installation site arrangements.

![Figure 9 PIU in MV Switchboard](image1)

![Figure 10 Rear View of Relay Panel](image2)

5.6. Conclusion

The IEC61850 process bus solution meets the performance requirements for protection and control system design, for the transformer feeder protection and control application. 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.

The sensitivity of the protection system is improved due to current sensing done nearest to the transformer.

CT burden gets reduced due to short CT cable length. This improves in CT sizing and hence cost, especially when it is GIS substation.

The relay is placed in panels’ remote to the switchgear. The protection panel contain almost no copper wiring except DC power and grounding, and is neat and clean solution. The design could be standardised and used for any transformer feeder protection and control application with minimal design inputs. This improves the protection life cycle significantly.

The relays are mounted in remote located panels from the switchgear. There are no high energy signals in the panels, as the only connection to the switchgear is a fibre optic cable. Hence it is safe to work on the system.
As there are very few electrical wiring and components, relay panel delivery period significantly gets improved. Relay panel design could be standardised and the assembly could be done at site. This improves the project timeline and the cost involved. The relay and its’ bricks could be tested together using a test bench.

The time and effort needed for future upgrades project is significantly reduced. Future upgrades will simply involve quick swap outs, and patching and unpatching between fibres optic cables.

There is no special training, learning, or background skills required beyond that of traditional protection and control skills.

Reliability of the protection of transformer feeder protection could be further improved by introducing protection 1 with process bus solution, and protection 2 with conventional overall differential schemes.

6. References

- Network Protection Application Guide (NPAG) by Alstom
- Power System Protection by P.M. Anderson, IEEE Series on Power Engineering
- HardFibre System Instruction Manual, GE Publication GEK-113500A
- An IEC 61850 Process Bus Solution by Pascal Schaub, Anthony Kenwrick, Powerlink, Australia
- Simplifying Protection System Design for Distribution substation by Stephen Hirsch, Rich Hunt, Jorge Cardenas and John Coursey; CIGRE Australia APB5

7. Abbreviations Used

HV – High Voltage
LV – Low Voltage
REF – Restricted Earth Fault
IDMT – Inverse Definite Minimum Time
SCADA – Supervisory Control And Data Acquisition
RTU – Remote Terminal Unit
PIU – Process Interface Unit
AIS – Air Insulated Substation