Economical Self-Powered Transformer Protection

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Abstract
Traditionally, substation transformer protection was provided by relayed circuit breakers or circuit-switchers, power fuses, or relayed-remote fault-interrupting schemes. Relayed protective schemes required an expensive substation control house and station batteries. Power fuses can only be applied where the continuous and fault-interrupting currents are within their more limited capabilities. A new transformer protective device was recently developed to address the short-comings of traditional protective measures. The device has high interrupting capacity similar to circuit breakers, and higher continuous current capacity than fuses. But, like power fuses, the new device derives power for fault sensing and tripping from the fault current itself – a relay control house is not required and the need for batteries and associated maintenance is eliminated, providing the most economical protection possible. Unlike power fuses, separate secondary neutral current sensing can be applied for more sensitive protection against ground faults and three-phase tripping is possible, even for single-phase faults.

The transformer protective device has a 31.5-kA interrupting rating and a total 5-cycle operating time. It is powered from the current transformers installed on the primary bushings of the transformer. It is furnished with a compact control cabinet, which contains three single-phase self-powered overcurrent relays, and optional fourth secondary neutral current relay. The electrically linked pole-units are lightweight and have minimal real estate requirements. In many cases, the device can be installed on the transformer, or on existing structures.

Introduction
The approach to substation transformer protection is a balancing act between system reliability, and the overall cost of the protection. In most cases these two characteristics are at opposite ends of the spectrum. The protection engineer must evaluate each installation to determine the balance between the required system reliability and the costs associated with the protection.

That balance is not the same for every substation application. A large substation transformer, larger than 50 MVA, supplying bulk load will warrant a greater level of protection. Traditionally, the larger transformers have been protected with a full complement of relays, such as, differential, overcurrent, and sudden pressure. These relays are typically powered from a dc source in a substation control house. It is desired to clear faults from the power system quickly and also to clear transformer internal faults as quickly as possible to minimize damage. Smaller distribution substation transformers, 12 MVA or less, generally do not warrant such sophisticated protection. Smaller transformers are often protected by fuses or some other less expensive means of protection in order to avoid the expense of the control house and the battery maintenance. Where fuses cannot be applied, other schemes have been applied to avoid expense. Transformers in the size range 15 to 50 MVA can be frustrating to protect, where they are larger than can readily be protected by fuses, but still small enough that expense of a full relayed circuit breaker scheme does not seem warranted. Schemes such as high-speed grounding (shorting) switches or remote tripping have been used. These methods still require a relaying scheme, although a pared-down relay scheme may be used. The expense of a station battery system was unavoidable.

Now there is a new protection alternative that takes advantage of relays powered from the output of the transformer primary bushing CTs. This option still eliminates the need for substation batteries, but it also provides more flexible protection for the transformer compared to other low cost alternatives. Applications of the new protective device include:

- **New substations.** By eliminating the need for virtually all auxiliary equipment, installed cost of transformer-protective equipment can be substantially reduced in a new substation.
- **Industrial-owned substations.** Such applications often do not require sophisticated protection. And, unlike power fuses, three-phase tripping is provided with re-settable pole-units, and a selection of TOC curves and settings. Plus, there’s no need to stock fuse units.
- **Rural substations.** Low initial costs can help these projects come in under budget.
- **Retrofit applications** where the available fault current has increased.
- **Upgrading protection for previous power fuse installations.** In these applications, the auxiliary equipment needed for a circuit breaker or a circuit-switcher—external relays, substation batteries, and a control house—is likely not present. The new device provides a very economical option to provide higher interrupting capacity, higher continuous current capacity, neutral current sensing, and three-phase tripping capability without the need for the expensive ancillary equipment.
- **Utilities with limited engineering resources.** A fully integrated protection package, pre-engineered and provided as a package, can be a significant benefit for utilities that have limited engineering staffs to devote to substation projects.
Economic and Reliability Considerations in Transformer Protection

Substation transformer protection can be provided remotely or locally. The method chosen can have significant economic and reliability implications. Reducing the cost of a substation transformer protective device hinges on minimizing the installed cost, while still providing adequate protection for the transformer. A large portion of the cost of a transformer protective device isn’t in the device itself, but in the support equipment, i.e. relays, instrument transformers, batteries, and the control house, needed to control the protective device.

Local Transformer Protection

Local protection is the preferred and most common method of transformer protection. Such arrangements utilize relayed circuit-switchers or circuit breakers, or power fuses.

Relayed Circuit-Switchers and Circuit Breakers

Circuit-switchers are commonly used for transformer protection. (See Figure 1.) Shown here in a typical primary-side transformer protection application, circuit-switchers are versatile devices that provide a number of advantages.

Circuit-switchers are relay-activated, thus providing more comprehensive protection than power fuses. They are also SCADA-compatible, unlike power fuses. Circuit-switchers provide back-up protection for secondary-side faults so there is no need to drop the entire transmission line. Circuit-switchers do, however, have a higher installed cost than power fuses and remote transformer protection schemes.

Circuit breakers are also used for transformer protection, as shown in this application diagram. (See Figure 2.) Like circuit-switchers, circuit breakers are relay-activated. Breakers offer higher interrupting ratings than power fuses and circuit-switchers, and they are SCADA-compatible. Their non-sealed interrupters can require field-filling with SF₆, which is undesirable given recent EPA initiatives to curb SF₆ emissions and record all usage. [1] SF₆ filling and reclamation equipment can be costly to service and maintain—many smaller utilities and industrial-owned substations do not own their own SF₆ filling equipment and must lease equipment when the need for filling arises. And SF₆ gas is costly, and like any compressed gas, takes training to handle safely—all important concerns when estimating the installed cost of a breaker.

![Figure 1. Circuit-switcher protection scheme.](image1)

![Figure 2. Circuit breaker protection scheme.](image2)

The high-speed reclosing feature of circuit breakers is neither necessary nor desirable for transformer protection. When a transformer primary-side protective device trips, a visit to the substation is usually in order in order to determine whether the transformer has been damaged. It is unlikely that a fault sensed by transformer protective relaying is temporary in nature, so high-speed reclosing into a faulted transformer could cause additional damage. The reclosing feature of circuit breakers adds cost without improving the quality of protection.

Power Fuses

Power fuses are low in cost, both initially and over the life of the device. Power fuses can be mounted nearly anywhere, minimizing real-estate requirements. They don’t need control power, eliminating yet another cost factor, and they have maintenance-free fusible elements. How-
ever, power fuses are not resettable. Thus, when a fuse operates, it must be replaced. The utility is therefore obliged to maintain an inventory of spare fuses. Power fuses are difficult to handle at higher voltages due to their size. And they can be difficult to coordinate with secondary-side devices, based on the limited selection of fuse characteristics. Power fuses provide single-phase operation only, and they are not available in interrupting ratings above 3000 MVA. (Figure 3) [2] [3]

Remote Transformer Protection
In remote transformer protection schemes, line-terminal circuit breakers are used to clear faults. Secondary faults are cleared by creating a bolted primary fault, typically using a grounding switch or a transfer-trip or sacrificial-switching scheme. (Figure 4, Figure 5, and Figure 6.) A disconnect switch is applied at the transformer to isolate the fault after it has been interrupted by the line-terminal breakers.

Remote protection schemes typically have low initial cost. But this advantage must be weighed against the decreased service reliability that results from their use. The entire transmission line is interrupted for all faults sensed by transformer protective relaying. In addition, such schemes take longer to clear faults because of the sequential operation of the local disconnect switch followed by operation of the line breakers. Equipment maintenance cost is high because of the need to maintain coordination among the devices. Further, these schemes subject the power system to high-magnitude faults, causing unnecessary stress and wear to equipment and further exacerbating the need for maintenance.

A main-secondary breaker or recloser is often applied in remote protection schemes to reduce the number of secondary faults that involve the entire transmission line. Its expense can offset much of the initial cost savings. For these reasons, remote protection schemes have become increasingly unacceptable.
Developing the Self-Powered Protective Device

Adapting the Relayed Circuit Switcher Design

The authors’ company initially developed a lower cost circuit-switcher replacement using a modular design approach. [4] It requires user-furnished control power and a trip signal from user-furnished relaying and sensing equipment. This design is similar to that of the interrupting unit of a Circuit-Switcher, but in this case, each pole-unit is self-contained with its own operating mechanism—the pole-units are filled with SF₆, and are of a sealed design. No field filling, or handling of SF₆ is required. Pole-units feature puffer-type interrupters and integral spring-charged operating mechanisms to attain a 31.5-kA fault-interrupting rating and a 3-cycle interrupting time. The trip signal from the user-furnished relaying actuates a solenoid in each operating mechanism, which releases the stored energy of the trip spring, to open the interrupter. Electrically signaling the pole-units to trip eliminates most simultaneity problems associated with a central mechanical drive and power train, and allows the device to achieve its 3-cycle interrupting time. And the fact that each pole-unit is manually reset avoids most of the costs associated with a switch operator containing a central operating mechanism. Considering the infrequency with which the transformer protector is expected to operate, the inconvenience of manually resetting the pole-units is minimal. The resetting procedure will be discussed in the operating procedure overview.

In developing the self-powered version, a self-powered overcurrent protection system was required that could adequately protect a distribution substation transformer and provide a trip signal capable of actuating the trip solenoids—while not adding excessive cost . . . neither in material cost nor maintenance and installation costs associated with a battery cabinet, or control house. See Figure 7.

Figure 7. Self-powered transformer protective device.

Development of the Trip-Energy Supply

One aspect of the design that allows for the capability of working with these relays is the development of a unique trip-energy supply (TES). The overall protective device has a low energy requirement that includes the use of metal-polyester capacitors, which is an extremely reliable new technology. The TES only requires 150 microfarads.

The trip-energy supply of the self-powered transformer protective device is powered from the output of primary-side bushing current transformers or stand-alone current transformers. Because of the low trip-energy requirements, the same CTs used for sensing the fault current also supply more than adequate energy for charging the tripping capacitors. [5] Proper CT selection will allow the trip-energy supply functions over a primary current range of 30 to 31,500 amperes. It is compatible with both 50-Hz and 60-Hz systems. The protection system is capable of sensing an overcurrent and providing a trip signal within 2 cycles at two times the pickup setting, for either a steady-state condition wherein the protection system is continuously powered and a fault subsequently occurs, or for a fault-closing condition wherein the protection system has not been continuously powered. The two-cycle power-up time plus 3-cycle operating time provides a total 5-cycle minimum interrupting time. The performance curve (Figure 8) illustrates the power-up time of the trip-energy supply at various CT output levels, for single-phase secondary current. A three-phase secondary current of as little as 350 mA will power up the trip-energy supply in 10 seconds.
Tripping is accomplished by releasing the energy from the trip-energy supply to the solenoids in the operating mechanisms. The trip-energy supply will not partially trip the pole-units. If for some reason there is not enough available energy to trip all three pole-units, operation of the device is blocked until the supply is fully charged. Under fault conditions, there will always be enough energy to trip the device.

The design also includes a manual trip device that is used to provide the trip energy, again without using a battery, for tripping tests during installation and commissioning, or any time it is desired to manually trip the pole-units when there is not enough current flowing through the CTs.

Overcurrent Protection System
The original design concept for the self-powered device called for an integral CT and an overcurrent control module built into each pole-unit. The relay would be programmed by attaching a PC to the serial connector on the control module. The design approach was rejected, however, because the overcurrent control module would be installed at line potential, and an outage would be necessary to change or test the relay settings. It is preferable for the relays to be at ground potential, for ease in setting and testing.

The overcurrent protection system that was selected consists of three single-phase overcurrent relays for time-overcurrent and instantaneous-overcurrent protection. A fourth overcurrent relay can be furnished to monitor residual current on the secondary-side of the transformer, for enhanced ground-fault protection. The relays normally provided feature a jumper switch that allows the relay engineer to select between various de-facto industry standard curve shapes. The relay cabinet can also contain other self-powered relays, if the application so requires. The relays operate in 2 cycles which, when added to the 3-cycle clearing time of the pole-units, provides a total fault-clearing time of 5 cycles.

The relays can be removed for setting and testing. If all four relays have been specified, each can be withdrawn for testing—one at a time—without losing protection. (On grounded-wye systems, only three relays are required at a given time to sense all types of faults.) [6]

Additional Inputs to the Protection System
Distribution substation transformers are frequently furnished with a sudden-pressure and/or a gas detection relay. If such relays do not require connection to the trip-energy supply for power for monitoring and providing a signal, they can be connected to the trip circuit of the self-powered protector.

A limitation of the current overcurrent protection system is that it cannot support current-differential relaying schemes that rely on powered relays. The self-powered device was designed without differential relays to preserve its ability to be self-powered. A study is underway to provide differential protection for the primary bus while maintaining the device’s self-powered feature.

Operating Procedure
The operating procedure for the self-powered transformer protective device is similar to that used when power fuses are applied. When the device has tripped, the load-side circuit breaker, switch, or recloser is opened. (If no load-side device is in place, the main-secondary circuit breaker or recloser is opened.) Then the line-side series disconnect is opened. Transformer inspection and maintenance can now be performed.

To restore service, the pole-units are manually closed and charged for opening with a charging tool provided with the device while the series disconnect switch is open. Each phase is charged separately. Thus, steps for visually verifying the charged status of each phase must be incorporated into the substation operating procedure. The relay targets are reset, and the line-side series disconnect is then closed, picking up transformer magnetizing inrush current. Then the load-side circuit breaker, switch, or recloser is then closed. In the rare event that the line-side disconnect is closed into a fault, the self-powered device is ready to trip-free and clear the fault.

Manual resetting takes only five minutes for the complete three-phase device. It requires clearance under the device. At certain mounting heights, extenders to the manual tool are required, or a platform or bucket truck must be used to reach the device with the manual tool. The trip-energy supply cannot provide enough power to allow for motorized resetting of the pole-units.

A line-side disconnect is required to pick up magnetizing inrush current in applications of power fuses and in applications of the self-powered device because of the
slow-speed resetting procedure. Single-phase replacement of fuses requires that the fuses be replaced with the transformer de-energized, and the single-pole manual resetting of the pole-units also requires that this operation be performed while the transformer is de-energized. But unlike power fuses, no time-current curve concession must be made with the self-powered device’s relays in the selection of a minimum-tripping curve above the inrush current of the transformer to avoid unnecessary fuse operations during energization.

Installation Procedure

The phases of the self-powered device are electrically linked for tripping. So, provided dielectric clearances are met, along with requirements for access to the pole-unit bases for charging, the pole-units can be mounted vertically at nearly any phase spacing. Since the pole-units are relatively light in weight compared to a circuit-switcher or circuit breaker, the foundation and structure requirements are minimal. Pole-units rated 69 kV weigh only 174 lbs. each. At 115 kV, they weigh 212 lbs. each and at 138 kV they weigh 217 lbs. each.

Application

Range of Transformers Protected

The self-powered device was specifically designed for application on distribution substation transformers. At 69 kV, it can protect up through a 30/40/50-MVA transformer. At 115 kV, it can protect up through a 37.5/50/62.5-MVA transformer and at 138 kV, it can protect up through a 50/66.5/83-MVA transformer. (At the upper extremes of these application ranges, there is some limitation as to the minimum impedance of transformer, so as to stay within the secondary fault rating of 2000 amperes.)

The self-powered protective device has a continuous current rating of 420 amperes, meeting the full-load current requirements of the aforementioned transformers. The higher continuous-current ratings of general-purpose circuit breakers are unnecessary for transformer-protection applications.

Based on ANSI Standard C57.12.10-1988, the full-load current of a 50-MVA transformer at 69 kV is 418 amperes. The full-load current of a 62.5-MVA transformer at 115 kV is 301 amperes. The full-load current of an 83-MVA transformer at 138 kV is 347 amperes. By tailoring the protective device’s ratings to the requirements of the application, the most economical design is provided.

The device has a 4200-ampere secondary-fault interrupting rating at 69 kV, and a 2600-ampere secondary-fault interrupting rating at 115 kV and 138 kV. To determine whether this secondary-fault rating is sufficient for a particular application, the following equation should be used:

\[
I = \frac{57.8P}{(\%Z)E}
\]

where

I = Inherent secondary-fault current, amperes (the secondary-side fault current as reflected on the primary side of the transformer, assuming an infinite, or zero-impedance source)

P = Transformer self-cooled three-phase rating, kVA

E = Primary-side system phase-to-phase voltage, kV

\(\%Z\) = Percent transformer primary-to-secondary impedance, referred to transformer self-cooled three-phase kVA rating

If the inherent secondary-fault current is 4200 amperes or less at 69 kV, or 2600 amperes or less at 115 kV or 138 kV, the device is suitable for the application. [7]

Example Applications

A common application of self-powered protective device is retrofitting for existing power fuses where the available fault current has increased, or is expected to increase in the future. The existing mounting structure of the power fuses is usually adequate for mounting the self-powered protective device without any significant modifications. Or the self-powered device can be mounted on the structure for the primary-side disconnect switch.

In the first example (Figure 9), a phosphate mine was expanding their operations and planned on bringing an additional set of 69-kV transmission lines into the facility. A new substation was sited on a ridge overlooking the tailing pond of the mine, in a remote area that will not be overly affected by flooding, or debris from the mining operation. The substation includes a 3.75/4.2-MVA transformer. By applying the self-powered device to protect the transformer, single-phasing issues associated with power fuses were eliminated. Also eliminated were the expense and maintenance associated with the control house that is normally required to control a relayed circuit breaker or circuit-switcher.
The self-powered device has also been applied on mobile transformers and in other temporary substation installations. In the next example (Figure 10), the utility was in the process of transferring part of their service area to another utility but, in the meantime, was responsible for providing service to an ethanol plant under construction. A 20-MVA mobile substation had been in place at the site for over six months. But the utility didn’t want to leave the mobile unit installed for the two years in which they were responsible for providing service. Instead, they decided to build a temporary substation, mounting the 138-kV self-powered protective device and manual disconnect switch directly on the tank of the 138-to 12-kV, 10/12-MVA transformer.

The control cabinet is installed directly on the side of the transformer. The transformer is mounted to railroad ties. It is planned to move the transformer by rail to another location after construction at the plant has been completed, and responsibility for the completed substation is transferred to the new utility.

References


