# Power Systems Engineering Research Center

**PSERC Background Paper**

# The Protection System in Bulk Power Networks

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September 8, 2003

Protection systems are found throughout society. Financial systems have “circuit breakers.” The human immune system is a very sophisticated protection system, and most of the symptoms of a cold are the results of this protection system. The congestion detection and handling mechanisms in Internet protocols could also be thought of as a “traffic breaker”. Finally, the bulk power system is protected from short circuits in the same way that household wiring is protected from short circuits. Fuses, circuit breakers and ground fault detectors are used in both.

In electric system protection systems, fuses are typically limited to distribution systems. Fuses can “blow” for a variety of reasons, such as downed distribution lines, unexpectedly high customer use, and short circuits due to animals coming in contact with conductors.

The operation of circuit breakers is more complicated than in the home. Besides the circuit breaker, protection equipment for a bulk power system consists of certain equipment for measuring electrical quantities (e.g., current and voltage sensors) and devices called relays. A relay is an intelligent device that reads appropriate electrical quantities (such as voltage, current, and frequency), and then, based on its logic settings, causes appropriate action to be taken. Relays can also take receive the electrical quantity information via communication channels.

Relays control the opening and subsequent reclosing of circuit breakers. A relay output trip signal is sent to circuit breakers when needed. As an example, the most common source of “faults” or short circuits in the transmission system is lightning. A lightning strike near a high voltage line produces an ionized path to ground that supports a large, damaging current to flow. Fault currents can be as large as tens of thousands of amps. The ionized arc dissipates when the line is deenergized, and the breakers can reclose and return the line to service. The time interval for such “high-speed” reclosing is typically 20 cycles or one-third of a second.

## Relays

There are thousands of relays in any system of any size. Each relay is designed to protect the piece of equipment it has been assigned from damage. The basic philosophy in protection system design is that any equipment that is threatened with damage by a sustained fault is to be automatically taken out of service. A fault (usually means a short circuit, but more generally refers to some abnormal system condition) occurs as a random event, usually an act of nature. Basic equipment needing protection consists of generators, transmission lines, transformers and systems nodes (or buses).

There are five basic types of relays in use[1]:

1. **Magnitude relays** that operate based on the magnitude of input quantities. Overcurrent relays are an example of this type of relay.

2. **Directional relays** respond to the phase angle difference between two AC quantities, for example, the phase angle of a sinusoidal current with respect to the phase angle of a sinusoidal voltage.

3. **Ratio relays** respond to the ratio of two phasor quantities. Phasor quantities are complex numbers representing the magnitude and phase angle of a 60 HZ sinusoid with respect to some reference. The ratio is therefore a complex number and the ratio relay may be designed to respond to the magnitude of the complex number or the complex number itself. The most common ratio relay is the impedance relay.

4. **Differential relays** respond to the magnitude of the algebraic sun of two or more inputs. The most common differential relay in use responds to the algebraic sum of currents entering a zone of protection and expects the sum to be zero.

5. **Pilot relays** use communicated information from remote sites as input signals.

When the power system was created, the first relays were electromechanical devices with moving mechanisms that made contact. Then, solid-state devices, with discrete electronic components, were introduced. These devices were ultimately followed by microprocessor-based relays.

Most existing microprocessor-based relays are stand-alone devices. But, as other devices (such as recording and control devices) in the substation become digital, an integrated substation architecture is emerging. The Utility Communication Architecture (UCA) envisions a local area network (LAN) in the substation for the various intelligent electronic devices and a router connecting the substation LAN to a fiber network constructed on the transmission line right-of-way. This utility Intranet would have to give data from relays a higher priority than other types of communications (such as power quality data) to provide the required relaying speed when a fault condition is detected. It

[1] See Phadke and Thorp, “Computer Telaying for Power Systems”, John Wiley.

has been estimated that there are tens of thousands of substations and up to 500,000 relays in North America.

## Relay Uses

Relays are used for protection. A zone of protection refers to a region in a power system with a defined set of equipment. A protection system consisting of one or several relays is made responsible for all faults occurring within the zone of protection.

*Protection of transmission lines*
Transmission lines can be protected on overcurrent. The activation value of an overcurrent relay is set between the maximum load current and the minimum fault current expected on the line. When a distance calculation is involved, impedance is calculated and used as the triggering or “pickup” quantity. Pilot relaying is used to protect a line when high speed protection of an entire line is desirable. Tie lines are usually protected by impedance relays but may be protected on overfrequency as well.

Because the transmission system is a three-phase system (whereas most homes use only one-phase), relays must deal with a number of possible faults. In a three-phase transmission system, there are three conductors (one for each phase) and a ground wire on the towers (in addition to the actual ground below). A short circuit between any two of these conductors caused by lightning, a tree, a failed insulator, etc. is a fault. Most faults are between a single conductor and ground (that is, a phase to ground fault). Even so, a protection system must be able to contend with all possible faults combinations.

More than one three-phase line can be supported by one set of towers. In most situations the relays must decide whether a fault is on the line the relay is protecting or on an adjacent line. In the former case the circuit breaker should open. In the latter case, the relay should not send a signal to the breaker. Signals from the remote end of the line can make this determination easier.

*Transformer protection*
Small transformers are usually protected by fuses or overcurrent relays. Large transformers (2.5 MVA or greater) are protected by circuit breakers operated by percentage current differential relays, overcurrent relays, temperature and pressure sensing equipment.

*Electrical side of generator protection*
Generally, protection of generators is not a system protection function but rather a plant protection function. Generators are protected against rotor heating caused by unbalanced stator currents and against loss of field current. There may be protection against reverse power, inadvertent energization, and out-of-step-protection as well. Frequency protection is backup protection for mechanical overspeed or underspeed conditions since speed is proportional to frequency.

*Bus protection*
Bus protection is designed to protect substations against fault conditions. Differential relaying is the primary tool.

*Other relay uses*
There are relays that perform control functions (as opposed to protection functions) in the system as well. For example, controlled islanding schemes, load shedding on overfrequency, and so on. In many systems, undervoltage relaying is used on critical busses to protect against voltage collapse. In a voltage collapse situation, frequency is too slow of an indicator. The undervoltage relay generally signals a predetermined load shedding operation when the magnitude of the bus voltage drops below a certain amount.

**Coordination of Relay Protection**

Coordination of relay protection is done to insure that only the equipment that is threatened with damage is taken out of service. Relay settings control when a relay sends a control signal to a circuit breaker. Relay coordination is the sequencing of those relay operations across relays in the system. For instance, with a fault along a transmission line, coordination would mean that the relay closest to the fault would operate before one further "upstream" does, thus reducing the outaged equipment to the smallest amount possible.

The coordination of relay protection functions is a difficult art. When analyzing a major event such as the August 14, 2003 blackout, determining all relay settings and whether or not each of them operated correctly is a time consuming and arduous task made even more difficult because the time tags are, more often than not, inaccurate or unsynchronized.

**Protection Philosophy and Relay Failures**

As noted above, the existing protection system, which evolved from a vertically-integrated utility structure, was designed to protect equipment, not the power system. The historical power system was generally robust enough that removing a transmission line or transformer from service caused no interruption in service to customers. The protection philosophy was to protect equipment because any disturbance would be brief and service would be quickly restored.

Protection system design is a much an art as it is a science. There are IEEE standards for suggested best design practices for all normal protection functions.

A relay has two failure modes. It can trip when it should not trip (a false trip) or it can fail to trip when it should trip. The two types of reliability have been designated as "security" and “dependability” by protection engineers. Dependability is defined as the measure of the certainty that the relays will operate correctly for all faults for which they are designed to operate. Security is the measure of the certainty that the relays will not operate incorrectly.

Present day relaying systems are also designed to be dependable at the cost of security. The existing protection system with its multiple zones of protection and redundant systems is biased toward dependability; for example, a fault is always cleared by some relays. There are typically two primary protection systems often relying on different principles (where one might depend on communications while the other only on local information) and multiple backup systems that trip (with some time delay) if both primary systems fail to trip. The result is a system that virtually always clears a fault. However, as a consequence, the protection system permits large numbers of false trips. When the transmission system is highly stressed or operated in different ways than designed, such under a restructured, market-based structure, the consequences of false trips can be serious.

**Protection System Failures in Disturbances**

The North American Electric Reliability Council (NERC) prepares an annual report of major disruptions in North America. Approximately ten to twenty major events are reported each year. The U.S. Department of Energy (DOE) established requirements for reporting electric system emergencies. In order to be reported, the disturbance must involve a certain number of customers or amount of interrupted customer load, and be of a specified duration:

Over a long historical period, more than 70% of the major disturbances involved relaying systems, not necessarily as the initiating event but contributing to the cascading nature of the event. For example, the 1965 Northeast Blackout was initiated by a relay tripping on load current. A number of relays failed to trip in the 1977 New York City Blackout. Also, there were incorrect relay operations in the multiple disturbances in the western U.S. in the Summer of 1996.

One manifestation of the backup systems described above is to divide the area the relay protects into zones. The first zone is the amount of the line for which the relay provides fast-primary protection. The second zone is the part of the system where the relay provides backup protection. Finally, the third zone protection amounts to backup of the backup. In addition to third zone trips, there have been incorrect generator trips resulting in the loss of needed generation.

Many of the incorrect relay operations can be characterized as “hidden failures.” Since relays are only called upon in unusual circumstances, there can be something wrong in the relay that is hidden until there are faults or heavy loads near the relay.

A number of hidden failures are attributed to maintenance. An example of the maintenance issue is the 1977 New York City Blackout where one of the relays involved in the blackout had been maintained a few weeks before the event. The last act in the maintenance procedure involved pushing a contact that was bent in the test and inadvertently left damaged.

Defects that are so serious that the relay would misoperate immediately when it was returned to service after maintenance are not “hidden.” Unfortunately hidden failures seem to account for a number of relay operations involved in major cascading outages.

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