IMPROVED RELAY COORDINATION AND FAULT DETECTION USING A NEW RELAY PLATFORM

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INTRODUCTION

This paper describes a new universal protective relay using modular hardware and software components that can be combined into numerous configurations. It improves protection and integrates different functions such as metering, control, PLC, and communication into a single device simplifying panel construction and reducing wiring costs. Protection is improved because this platform makes it possible to manipulate input voltage and current samples through different algorithms to obtain various quantities such as phasors, symmetrical components, and frequency, which combined make faster and more accurate decisions about faults in the system. Additionally, this relay has low input burden and allows the use of low-output voltage and current sensors with improved measuring characteristics compared to conventional instrument transformers. This platform can be used as a single model intelligent electronic device (IED) throughout a utility for any type of protection, control, or metering. The PC-based software comprises both an intuitive graphical interface for the relay functions and a Computer-Aided Engineering (CAE) program for designing and testing protection, control, and monitoring schemes. Any software changes to the protection scheme are self-documenting, since the relay cannot perform any function not visually drawn in the CAE package [1]. Relay and control systems can be rapidly developed for specific applications rather than adapting one or more fixed function products to fit a given application. Troubleshooting is simplified because event records can be examined and played back in the PC software "version" of the actual hardware, permitting examination of the behavior of every level of the implemented relay and control system.

This paper demonstrates the overall characteristics of this universal relay platform by discussing all topics mentioned in the previous paragraph. The next section compares the protection designs between electromechanical and static relays and microprocessor-based relays; also compared are methods and levels of integration of protection, control, and monitoring functions between current-technology microprocessor relays and the new universal relay. The following section describes a new universal protective relay architecture. The final section of this paper describes a relay scheme developed for distribution systems to compare the coordination and fault detection effectiveness of the new universal relay platform and traditional relay schemes.

PROTECTIVE RELAYING DESIGN METHODS

Figure 1 presents a traditional protective scheme employing electromechanical metering and protective devices. This scheme requires separate current transformers (CTs) for metering and protection. Metering CTs are designed to be accurate under normal operating conditions. Their V-I saturation level is low since metering accuracy is not important during faults, and the saturated CTs protect metering equipment against high current faults.

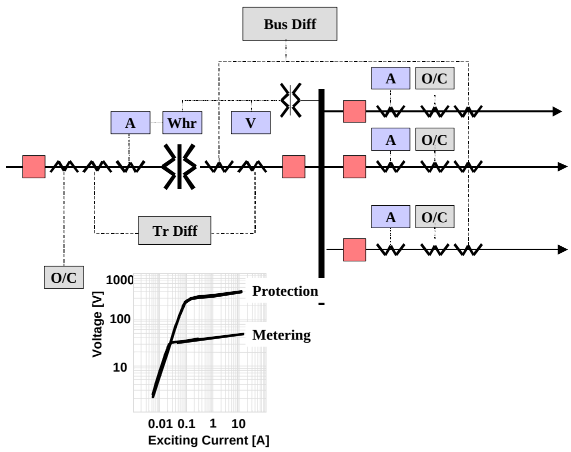

Figure 1. A Typical Protection and Measurement Design using Electromechanical Protection and Measuring Devices

The protection CTs are less accurate than the metering CTs, but their saturation level is high so that the CTs can accurately replicate high fault currents to enable correct protection operation. Electromechanical relay burden is high and one CT cannot drive all of the protective relays at a site. Different protection functions require different CTs.

Microprocessor-based equipment with its inherently low burden has made the high power output of CTs unnecessary and the use of other measurement transducers possible. One such measuring device that does not produce high power output but offers many advantages over CTs is the Rogowski coil. Rogowski coils have high measurement accuracy (they can be designed to be better than 0.1%, but are typically 1%-3%) and wide measurement range (the same coil can be used to measure currents from several amps to hundreds of kilo amps). Rogowski coils do not measure direct currents but, unlike CTs, they can accurately measure currents when a large DC component is present because they are not constructed with a saturable iron core. They also have a wide frequency range - typically 0.1 Hz to over 1 MHz (depending on design), can withstand unlimited short-circuit currents; can be very small to allow measurement of currents in restricted areas; can be flexible or rigid depending on application requirements; can be used to measure current distributions in circuits having very small impedances without affecting the circuits; are galvanically isolated from the primary conductor; and have low production cost [2]. Another possible current sensor is the optical CT [3]. On-going developments in this area include Faraday effect (magneto-optic) based devices, devices using silica optical fiber, and CT or shunt devices using fiber-optical cables. Conventional CTs or current sensors when used with microprocessor-based equipment can combine measurements and protection and significantly reduce the required number per design. Voltage transformers can also be replaced by low power voltage sensors (resistive or capacitive dividers) [4].

Electromechanical protective devices have inflexible operational characteristics. Engineers need to study relay application criteria in detail before ordering an electromechanical relay because its operational characteristics cannot be changed. For example, an overcurrent relay with normal time-current curves (TCCs) is not readily changed into a relay with extremely inverse TCCs, and is impossible to change into a frequency relay.

Directional ground-fault protection operating angles depend on the power transformer's neutral connection. For ungrounded systems, fault current flows back to the source through the stray capacitances of the healthy phases, and the phase difference between voltage and ground-fault current is 90 degrees. For solidly and resistively grounded systems, ground-fault current returns back to the source through the transformer neutral. The phase difference between voltage and ground-fault current is 0 degrees in resistively grounded systems and 30 degrees to 60 degrees in solidly grounded systems. Electromechanical relays are designed with one fixed operating angle and require different relays for different neutral treatment and system characteristics.

Earlier microprocessor relays introduced a high degree of flexibility because they provided a number of different operational characteristics in the same chassis. One relay could and does satisfy many applications. But different protective functions still require different relays. Metering and control functions also require different hardware (Figure 2a). New technologies introduce the capability to integrate protection, monitoring, and control functions, all designed in a single software program and downloaded to a single hardware platform (Figure 2b).

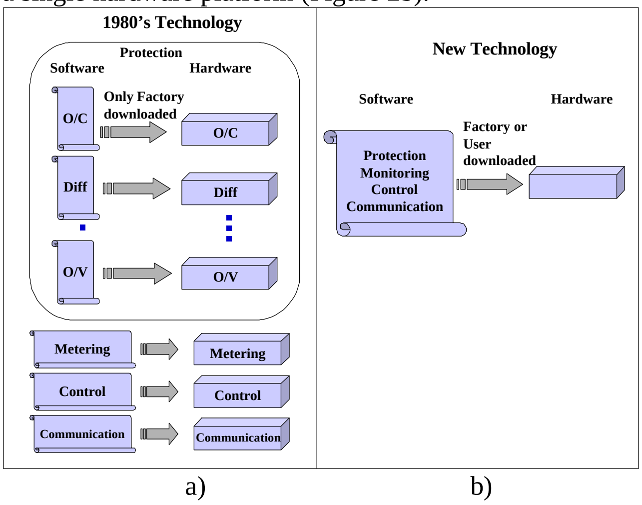

Figure 2. Protection, Monitoring, and Control Functions with Microprocessor Relays (a) and with New Technologies (b)

Multiple Setting Groups (MSG) is a unique feature in modern relays which is unavailable with older technology, i.e., electromechanical and solid-state relays. Older relays were constrained to perform protective functions based on a single group of settings. MSGs permit the protective device to run its programmed scheme with one of several active-setting groups. The individual settings-several dozen in number depending on the complexity of the scheme-are arranged in perhaps 5 to 10 parallel groups. Any one particular setting group may be instantly activated to replace the previous values. Selection of the active group is typically performed in the relay by generating a binary number whose bits consist of designated relay contact inputs.

Using the example of distribution feeder protection, MSGs may be used to adjust the overcurrent pickup values, inverse timing functions, reclose sequences and the status (enabled, disabled) of protective elements such as ground trip.

Applications with MSGs are too varied to discuss. But some utilities use a separate MSG for each major season of the year, for special contingency or restoration conditions, or for maintenance activity.

In addition to active intervention by a user either locally or remotely via the relay's contact inputs, MSG selection may (depending on the protective device) be performed via communication (ModBus, UCA, or other). MSGs can be employed to construct adaptive schemes whereby quantities internal to the relay, for example, demand current above a threshold may be used as the logic signal to drive selection of the proper MSG.

Multiple protection functions in digital relays permit the interconnection of components within the embedded software, instead of external to the relay. This significantly reduces external wiring compared to traditional discrete devices, offering considerable cost savings in panel construction and wiring. The "integration" task needs to be performed only one time when composing the software embedded in the particular digital relay type; then is readily available for all of the applications of that relay type. The panel construction and wiring for all individual components is entirely avoided. Figures 3 and 4 compare panel views and secondary wiring for protection and measurement using traditional and new technology designs for two feeders, but the same comparison can be extended for a whole substation.

Secondary wiring can be further reduced using fiber-optical cables or relays tied together in a local area network (LAN) with MMS protocol over an Ethernet.

One hardware with software can integrate protection and measurement for one feeder, or in some applications, more feeders, while a second hardware with software can integrate backup protection for more feeders or a whole substation.

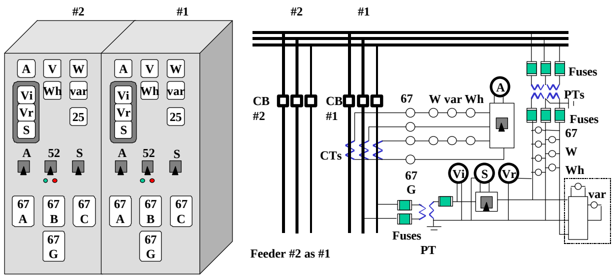

Figure 3. Panel View and the Secondary Wiring for Traditional Designs

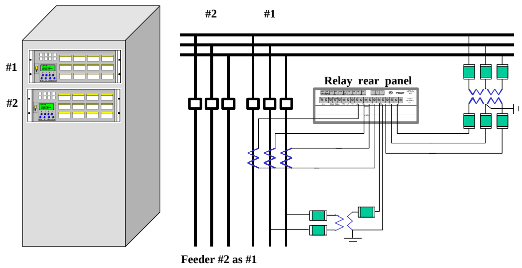

Figure 4. Panel View and the Secondary Wiring for Designs using New Technologies

To expand the scope of protective relay functions across traditional boundaries, additional hardware is generally required. For example, to integrate another zone of protection into a digital relay requires only the alteration of software, but to add panel meters or transducers requires dedicated additions and modifications to the hardware as well. Also, considerable time is involved in developing the embedded firmware for new applications. To satisfy this, some relays attempt to become all things to all applications, ostensibly expanding the demand for the device. But, this may increase the complexity of the relay such that it becomes difficult to understand its operation, testing and use. It is common for users to manually turn off dozens of embedded features unnecessary for a given application.

The new modular architecture does not face these same problems. If a particular capability is warranted–even on a per-application basis–then the appropriate additional hardware or software can be more easily justified. If a capability is not needed, it adds no cost to the relay.

From a system protection standpoint, the ideal protective relay should be optimally designed for each application. *From a cost perspective*, the ideal protective relay should be identical everywhere, greatly simplifying manufacturing and maintenance. *From a practical standpoint*, the ideal protective relay should share as much as possible between applications, and from there be customized with as little effort possible to minimize the sum of production, application, and maintenance cost.

A UNIVERSAL PROTECTIVE RELAY ARCHITECTURE

The relay architecture presented in this paper integrates protection, control, event management, relay simulation, and user-interface functions in the same package [5,6]. The graphical CAE running on IBM-compatible personal computers under the Microsoft Windows operating system is used to develop protective relay schematic diagrams. The software then automatically translates the schematic into a form readable by the hardware platform.

The highest-level functional blocks for this relay are shown in Figure 5. The scheme is modular and can be pre-configured explicitly for a given application, for example distribution protection. Also, since the scheme is an open, user-programmable universal relay platform, it can be easily modified for the user's particular application.

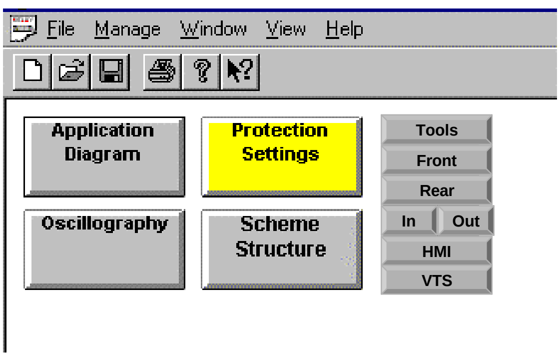

Figure 5. The Relay High-Level Functional Blocks

The schematic is composed of blocks, representing various operations to be performed on signals. Several blocks can be easily bound together into a compound block or module which embodies the processing required to implement a more complicated function. Such compound function blocks can then be connected into the schematic. Compound blocks can be further nested and bound together with other simple and compound blocks to compose yet more sophisticated functions. The created schematic diagrams are thus termed hierarchical. The most sophisticated function blocks are usually hierarchical modules containing layers of simple and yet more simple function blocks. The great advantage of modularity in software is that modules can be built, tested, and maintained separately from the whole software. That is, it is not necessary for all the many pieces to be fully functioning together before they can each perform their individual function. Any functions that are constructed graphically and packaged together in a single container can be saved to a file for future use. Thus, the effort expended in developing and qualifying a given module need not be duplicated. Figure 5 shows a high-level scheme that includes four main blocks: application diagram, protection settings, oscillography, and scheme structure.

The Application diagram includes a single-line diagram, measurements, and the recloser/breaker status for intuitive online viewing. The application block can be opened by clicking the mouse (Figure 6). The online view mode displays ongoing real-time values. The mode can be activated whenever the user's PC is in communication with the relay. This is a valuable benefit during relay commissioning and testing, since it is possible to monitor the actual operational state of all internal elements as input conditions are applied or adjusted. During normal operation, the application diagram can be used to determine the status of a protection scheme under load conditions. For example, the degree to which load level or load imbalance affect protection characteristics can be determined. This can be directly observed using the online view, by simply examining the inputs and outputs of the internal protective relay elements. All elements whose status has been changed turn colors from green to red and from "0" to "1".

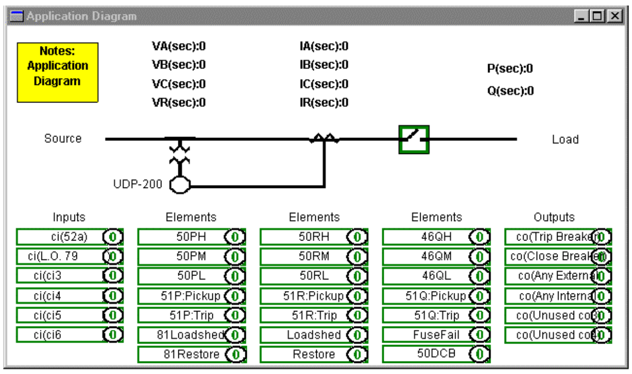

Figure 6. Application Diagram and On-Line View

Setting the relay is performed by opening the Protection Setting block (see Figure 5) and typing the appropriate values in the window.

Multiple Function-Specific Oscillography. The scheme includes multiple function-specific oscillographic view for overview or focused analyses of event records. Figure 7 shows oscillographic boxes for phasor plots and phasor waveform analyses that have been opened. Phasor plots provide a graphical representation of instantaneous phasor relationships. Oscillographic report formats provide an intuitive visual overview of system conditions and relay responses.

The Scheme Structure. The Scheme Structure block contains the relay scheme. It can be secured against unauthorized changes by implementing the access levels. The seven smaller blocks shown in Figure 5 are supporting tools in the scheme design. A scheme can be built by selecting, clicking and dragging pre-designed elements located in the tools block. "Front" and "Rear" blocks include virtual views of the relay front and rear panels. The Rear panel view displays which terminal and contacts are used. Another contact can be added by clicking and dragging an available contact icon from the "Rear" block.

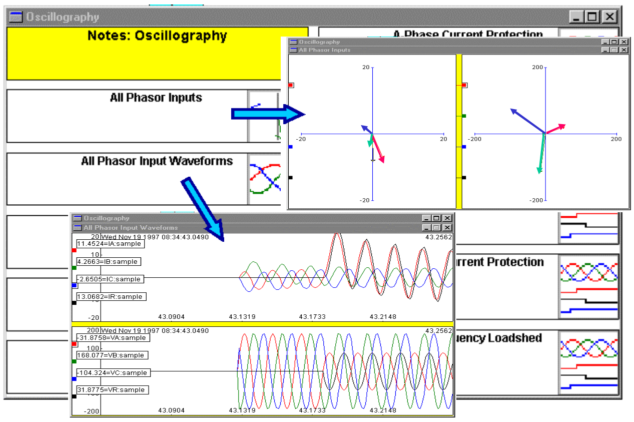

Figure 7. Multiple Function-Specific Oscillography showing Phasor Plots and Phasor Waveform Windows Open

The Virtual Test Set (VTS) model is programmed in the relay software. It models the simplified system shown in Figure 8, including a voltage source, source impedance, and line impedance. Various faults, system parameters, and fault incidence angles can be modeled. It provides the ability to conveniently verify that the software design has the intended functional characteristics. Virtual test capabilities are encapsulated within each and every input module. Thus, the relay automatically has built-in test capabilities with as many independent and matched signal sources as there are relay inputs, analog or contact. A virtual test signal does not pass through the various output components of a conventional test set. Digital-to-analog converters, transducers, filters, transformers, and amplifiers can all contribute to signal inaccuracy at the relay input terminals, and these potential sources of error are entirely eliminated in a virtual test.

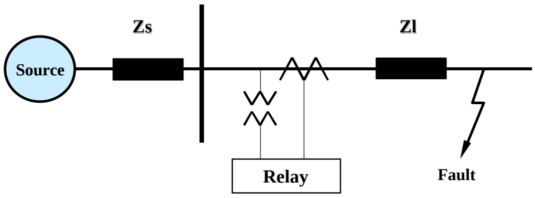

Figure 8. VTS Representing System Model

The Human-Machine-Interface (HMI) is a display on the relay front panel which can be programmed according to users' exact needs. It can include recloser/breaker status, target outputs, external alarms, recloser/breaker control (closing and opening), and measurement.

Troubleshooting and Outage Analysis

Relay event records of interest can be uploaded to personal computers. The active schematic permits examination of relay inputs and outputs, operation of every internal relay element in-between, and the complex logic that combines them. If the cause of a relay operation is not known, the active schematic can be examined to determine the cause. Analyses of relay operations and outages can be accomplished by uploading the event records and replaying them. It is possible to investigate how relay settings influence relay operation. Settings can be modified with a personal computer and then tested by replaying an actual fault record with the modified settings. With this capability, it can be predicted how the relay will perform in the field, and how it will perform in the future. The relay in the field can effectively be re-tested with an exact duplication of recorded input conditions.

Outage analysis or relay testing can be performed on an identical scheme on the user's computer without affecting the relay setting or connections. If tests must be performed on the actual relay, then after tests are completed, the relay becomes *automatically* fully functional by downloading the scheme containing all settings, contact outputs, and other programmed parameters. This eliminates the possibility for the user to overlook implementing specific parameters.

PROTECTION OF DISTRIBUTION SYSTEMS

To demonstrate the practical application of this relay platform for distribution feeder protection, a Universal Distribution Protection (UDP) scheme was developed which includes:

- Inverse time-overcurrent protection for phase, negative-sequence, and zero-sequence current, improving relay sensitivity and reliability for different fault types. Symmetrical components are calculated in the Symmetrical Component Filters block shown opened in Figure 9. As previously described, schemes can be built by selecting, clicking and dragging pre-designed elements located in the tools block (Figure 5). The Symmetrical Component Filters block includes input signals (current phasors), a block for symmetrical component calculations, a block to filter symmetrical component magnitudes for use by inverse-time overcurrent elements elsewhere in the scheme, and output signals (symmetrical components, phasors and magnitudes). Signals flow in the relay scheme from one block to another. For example, the output signals for Phase Currents block (phase currents) became the input signals for the Symmetrical Component Filters block, and then the output signals of the Symmetrical Component Filters block become the input signals for the other blocks, and so on.
- Instantaneous and time-delayed overcurrent in three levels for all phases and all symmetrical components. The first level provides coordination with high current faults at the beginning of line, the second level coordinates for low current faults at the line end. The third level monitors the protected line for low current events, such as arcing, for reporting back to the operator center.
- Negative-sequence directional element for unbalanced faults, positive-sequence directional element for balanced faults. These can be enabled on a per zone basis for coordination in looped systems or ungrounded systems. Any time-overcurrent function and any overcurrent zone can be set independently to act as directional forward, directional reverse, or non-directional.
- Programmable reclosing with advanced capabilities for sequence coordination, and shot-dependent and fault-dependent fast-reclosing and fast-tripping.
- Under-frequency load shedding and restoration. This function disconnects load during disturbances supporting the system stability and closes the load back after the system recovers.
- Sub-cycle overcurrent protection for self-clearing faults. A number of cable failures have been possibly caused by water penetrating into cable splices resulting in insulation breakdown followed by an arc. Arcing causes fast water evaporation and develops high pressure inside the splice which extinguishes the arc and interrupts current within a quarter cycle. Because the fault current is interrupted by the water vapor pressure developed, these types of faults are called self-clearing faults. Their occurrence progresses in time until the splice fails and damages the cable.

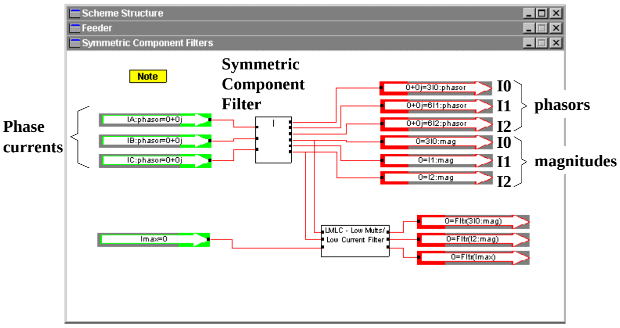

Figure 9. Symmetrical Component Filters Block in the Relay Scheme

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