B1

Relay Technology

Network Protection & Automation Guide

Life Is On | Schneider Electric

Chapter B1

Relay Technology

B1

1. Introduction

Since the 1960s there have been enormous changes in relay technology. The electromechanical relay in all of its different forms has been replaced successively by static, digital and numerical relays, each change bringing with it reductions in size and improvements in functionality. At the same time, reliability levels have been maintained or even improved and availability significantly increased due to techniques not available with older relay types. This represents a tremendous achievement for all those involved in relay design and manufacture.

This chapter charts the course of relay technology through the years. As the purpose of the book is to describe modern protection relay practice, it is natural to concentrate on digital and numerical relay technology. The vast number of electromechanical and static relays are still giving dependable service, but descriptions on the technology used must necessarily be somewhat brief.

2. Electromechanical relays

These relays were the earliest forms of relay used for the protection of power systems, and they date back nearly 100 years. They work on the principle of a mechanical force causing operation of a relay contact in response to a stimulus. The mechanical force is generated through current flow in one or more windings on a magnetic core or cores, hence the term electromechanical relay. The principle advantage of such relays is that they provide galvanic isolation between the inputs and outputs in a simple, cheap and reliable form – therefore for simple on/off switching functions where the output contacts have to carry substantial currents, they are still used.

Electromechanical relays can be classified into several different types as follows:

a. attracted armature

b. moving coil

c. induction

d. thermal

e. motor operated

f. mechanical

2.1 Attracted armature relays

These generally consist of an iron-cored electromagnet that attracts a hinged armature when energised. A restoring force is provided by means of a spring or gravity so that the armature will return to its original position when the electromagnet is de-energised. Typical forms of an attracted armature relay are shown in Figure B1.1. Movement of the armature causes contact closure or opening, the armature either carrying a moving contact that engages with a fixed one, or causes a rod to move that brings two contacts together. It is very easy to mount multiple contacts in rows or stacks, and hence cause a single input to actuate a number of outputs. The contacts can be made quite robust and hence able to make, carry and break relatively large currents under quite onerous conditions (highly inductive circuits). This is still a significant advantage of this type of relay that ensures its continued use.

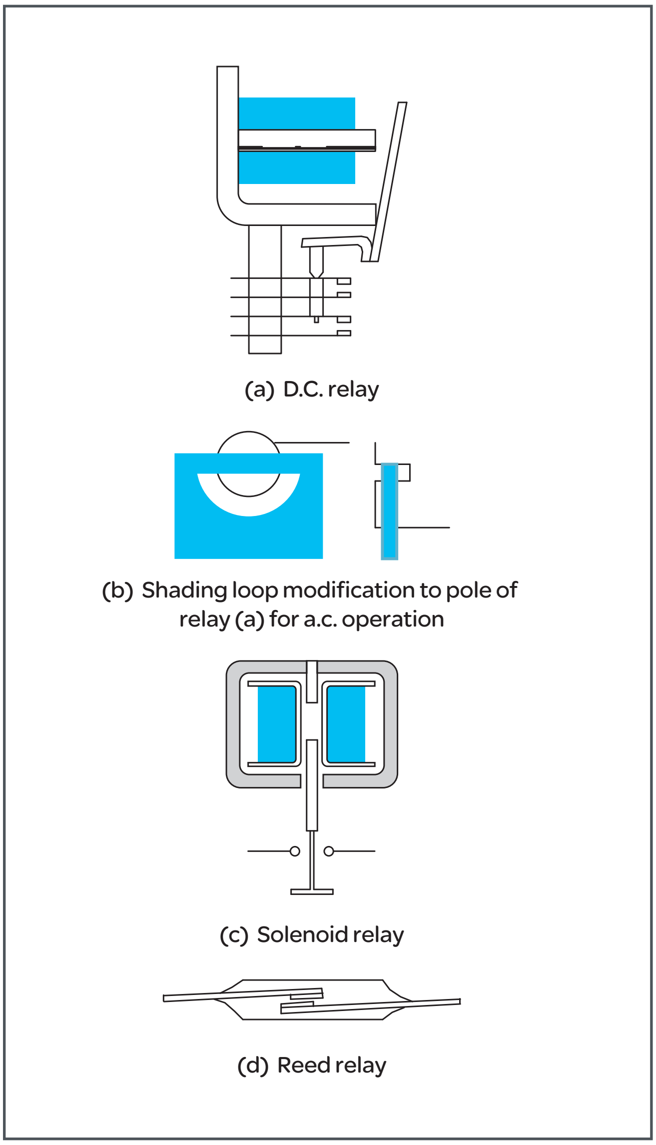


Figure B1.1:
Typical attracted armature relays

2. Electromechanical relays

The energising quantity can be either an a.c. or a d.c. current. If an a.c. current is used, means must be provided to prevent the chatter that would occur from the flux passing through zero every half cycle. A common solution to the problem is to split the magnetic pole and provide a copper loop round one half. The flux change is now phase-shifted in this pole, so that at no time is the total flux equal to zero. Conversely, for relays energised using a d.c. current, remanent flux may prevent the relay from releasing when the actuating current is removed. This can be avoided by preventing the armature from contacting the electromagnet by a non-magnetic stop, or constructing the electromagnet using a material with very low remanent flux properties.

Operating speed, power consumption and the number and type of contacts required are a function of the design. The typical attracted armature relay has an operating speed of between 100ms and 400ms, but reed relays (whose use spanned a relatively short period in the history of protection relays) with light current contacts can be designed to have an operating time of as little as 1msec. Operating power is typically 0.05-0.2 watts, but could be as large as 80 watts for a relay with several heavy-duty contacts and a high degree of resistance to mechanical shock.

Some applications require the use of a polarised relay. This can be simply achieved by adding a permanent magnet to the basic electromagnet. Both self-reset and bi-stable forms can be achieved. Figure.B1.2 shows the basic construction. One possible example of use is to provide very fast operating times for a single contact, speeds of less than 1ms being possible.

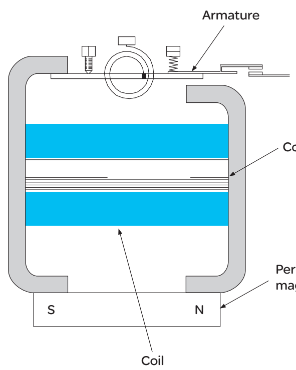


Figure B1.2:
Typical polarised relay

3. Static relays

The term ‘static’ implies that the relay has no moving parts. This is not strictly the case for a static relay, as the output contacts are still generally attracted armature relays. In a protection relay, the term ‘static’ refers to the absence of moving parts to create the relay characteristic.

Introduction of static relays began in the early 1960’s. Their design is based on the use of analogue electronic devices instead of coils and magnets to create the relay characteristic. Early versions used discrete devices such as transistors and diodes in conjunction with resistors, capacitors, inductors, etc., but advances in electronics enabled the use of linear and digital integrated circuits in later versions for signal processing and implementation of logic functions. While basic circuits may be common to a number of relays, the packaging was still essentially restricted to a single protection function per case, while complex functions required several cases of hardware suitably interconnected. User programming was restricted to the basic functions of adjustment of relay characteristic curves. They therefore can be viewed in simple terms as an analogue electronic replacement for electromechanical relays, with some additional flexibility in settings and some saving in space requirements. In some cases, relay burden is reduced, making for reduced CT/VT output requirements.

A number of design problems had to be solved with static relays. In particular, the relays generally require a reliable source of d.c. power and measures to prevent damage to vulnerable electronic circuits had to be devised. Substation environments are particularly hostile to electronic circuits due to electrical interference of various forms that are commonly found (e.g. switching operations and the effect of faults). While it is possible to arrange for the d.c. supply to be generated from the measured quantities of the relay, this has the disadvantage of increasing the burden on the CT’s or VT’s, and there will be a minimum primary current or voltage below which the relay will not operate. This directly affects the possible sensitivity of the relay. So provision of an independent, highly reliable and secure source of relay power supply was an important consideration. To prevent maloperation or destruction of electronic devices during faults or switching operations, sensitive circuitry is housed in a shielded case to exclude common mode and radiated interference. The devices may also be sensitive to static charge, requiring special precautions during handling, as damage from this cause may not be immediately apparent, but become apparent later in the form of premature failure of the relay. Therefore, radically different relay manufacturing facilities are required compared to electromechanical relays. Calibration and repair

3. Static relays

is no longer a task performed in the field without specialised equipment. Figure B1.3 shows the circuit board for a simple static relay. An example of static relay is shown in Figure B1.4.

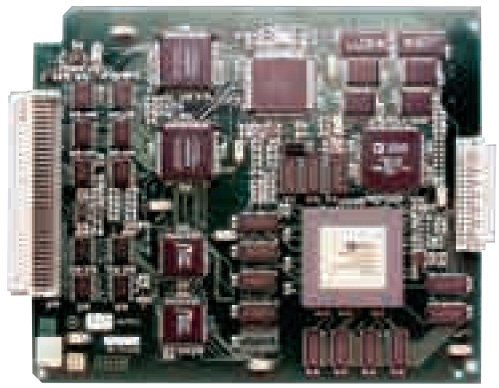


Figure B1.3:
Circuit board of static relay

Figure B1.4:
Example of static relay

4. Digital relays

Digital protection relays introduced a step change in technology. Microprocessors and microcontrollers replaced analogue circuits used in static relays to implement relay functions. Early examples began to be introduced into service around 1980. However, such technology has been completely superseded by numerical relays.

Compared to static relays, digital relays introduce Analogue to Digital (A/D) conversion of all measured analogue quantities and use a microprocessor to implement the protection algorithm. The microprocessor may use some kind of counting technique, or use the Discrete Fourier Transform (DFT) to implement the algorithm. However, the typical microprocessors used have limited processing capacity and memory compared to that provided in numerical relays. The functionality tends therefore to be limited and restricted largely to the protection function itself. Additional functionality compared to that provided by an electromechanical or static relay is usually available, typically taking the form of a wider range of settings, and greater accuracy. A communications link to a remote computer may also be provided.

The limited power of the microprocessors used in digital relays restricts the number of samples of the waveform that can be measured per cycle. This, in turn, limits the speed of operation of the relay in certain applications. Therefore, a digital relay for a particular protection function may have a longer operation time than the static relay equivalent. However, the extra time is not significant in terms of overall tripping and possible effects of power system stability. An example of a digital relay is shown in Figure B1.5.

Figure B1.5:
Example of digital relays

5. Numerical relays

The distinction between digital and numerical relay rests on points of fine technical detail, and is rarely found in areas other than Protection. They can be viewed as natural developments of digital relays as a result of advances in technology. Typically, they use either a specialised digital signal processor (DSP) as the computational hardware or a high performance microcontroller, together with the associated software tools. The input analogue signals are converted into a digital representation and processed according to the appropriate mathematical algorithm.

In addition, the continuing reduction in the cost of microprocessors and related digital devices (memory, I/O, etc.) naturally leads to an approach where a single item of hardware is used to provide a range of functions ('one-box solution' approach). By using multiple microprocessors to provide the necessary computational performance, a large number of functions previously implemented in separate items of hardware can now be included within a single item. Table B1.1 provides a list of typical functions available, while Table B1.2 summarises the advantages of a modern numerical relay over the static equivalent.

Distance Protection (several schemes including user definable)
Overcurrent Protection (directional/non-directional)
Several Setting Groups for protection values
Switch-on-to-Fault Protection
Power Swing Blocking
Voltage Transformer Supervision
Negative Sequence Current Protection
Undervoltage Protection
Overvoltage Protection
CB Fail Protection
Fault Location
CT Supervision
VT Supervision
Check Synchronisation
Autoreclose
CB Condition Monitoring
CB State Monitoring
User-Definable Logic
Broken Conductor Detection
Measurement of Power System Quantities (Current, Voltage, etc.)
Fault/Event/Disturbance recorder

Table B1.1:
Numerical distance relay features

Several setting groups
Wider range of parameter adjustment
Remote communications built in
Internal Fault diagnosis
Power system measurements available
Distance to fault locator
Disturbance recorder
Auxiliary protection functions (broken conductor, negative sequence, etc.)
CB monitoring (state, condition)
User-definable logic
Backup protection functions in-built
Consistency of operation times - reduced grading margin

Table B1.2:
Advantages of numerical protection relays over static

Figure B1.6 shows typical numerical relays, and a circuit board is shown in Figure B1.7. Figure B1.8 provides an illustration of the savings in space possible on a HV feeder showing the space requirement for relays with electromechanical and numerical relay technology to provide the same functionality.

Figure B1.6:
Typical numerical relays

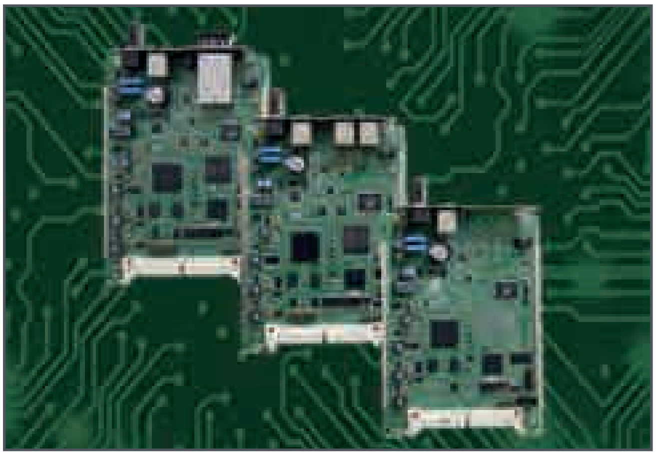


Figure B1.7:
Circuit board for numerical relay

Figure B1.8 :
Space requirements of different relay technologies for same functionality

5. Numerical relays

Because a numerical relay may implement the functionality that used to require several discrete relays, the relay functions (overcurrent, earth fault, etc.) are now referred to as being 'relay elements', so that a single relay (i.e. an item of hardware housed in a single case) may implement several functions using several relay elements. Each relay element will typically be a software routine or routines.

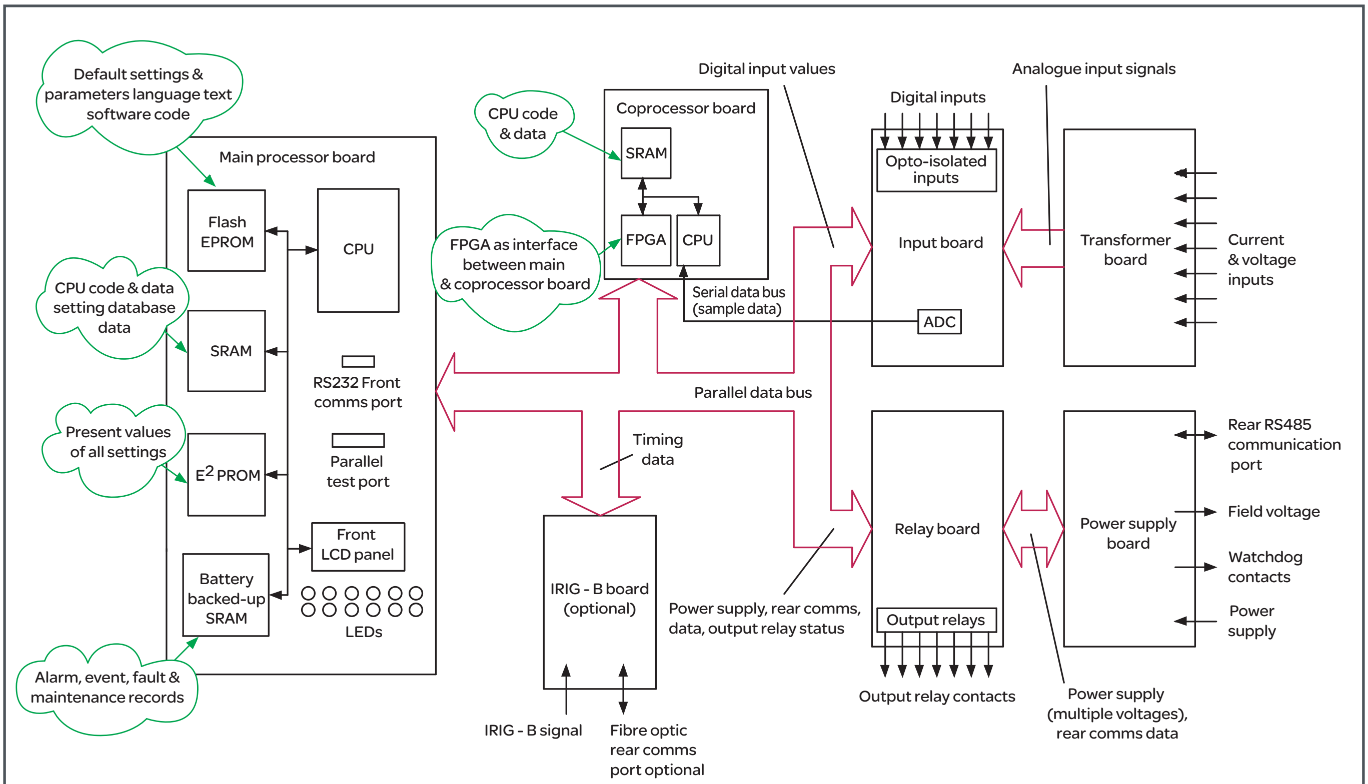
The argument against putting many features into one piece of hardware centres on the issues of reliability and availability. A failure of a numerical relay may cause many more functions to be lost, compared to applications where different functions are implemented by separate hardware items. Comparison of reliability and availability between the two methods is complex, as inter-dependency of elements of an application provided by separate relay elements needs to be taken into account.

With the experience gained with static and digital relays, most hardware failure mechanisms are now well understood and suitable precautions taken at the design stage. Software problems are minimised by rigorous use of software design techniques, extensive prototype testing (see Chapter [E1: Type Testing, Offer Safety and Reliability]) and the ability to download amended software into memory (possibly using a remote link for download). Practical experience indicates that numerical relays are at least as reliable and have at least as good a record of availability as relays of earlier technologies. In addition relays are now available that are certified for Safety Integrity Level 2.

An overview of the concepts behind a numerical relay is presented in the following sections.

5.1 Hardware architecture

The typical architecture of a numerical relay is shown in Figure B1.9. It consists of one or more DSP microprocessors, some memory, digital and analogue input/output (I/O), and a power supply. Where multiple processors are provided, it is usual for one of them to be dedicated to executing the protection relay algorithms, while the remainder implements any associated logic and handles the Human Machine Interface (HMI) interfaces. By organising the I/O on a set of plug-in printed circuit boards (PCBs), additional I/O up to the limits of the hardware/software can be easily added. The internal communications bus links the hardware and therefore is critical component in the design.



Legend:

SRAM - Static Read Only Memory
CPU - Central Processing Unit
IRIG-B - Time Synchronisation Signal
FPGA - Field Programmable Logic Array
ADC - Analogue to Digital Converter
E^2PROM - Electrically Erasable Programmable Read Only Memory
EPROM - Electrically Programmable Read Only Memory
LCD - Liquid Crystal Display

Figure B1.9:
Relay modules and information flow

It must work at high speed, use low voltage levels and yet be immune to conducted and radiated interference from the electrically noisy substation environment. Excellent shielding of the relevant areas is therefore required. Digital inputs are optically isolated to prevent transients being transmitted to the internal circuitry. Analogue inputs are isolated using precision transformers to maintain measurement accuracy while removing harmful transients. Additionally, the input signals must be amplitude limited to avoid them exceeding the power supply voltages, as otherwise the waveform will appear distorted, as shown in Figure B1.10.

Analogue signals are converted to digital form using an A/D converter. The cheapest method is to use a single A/D converter, preceded by a multiplexer to connect each of the input signals

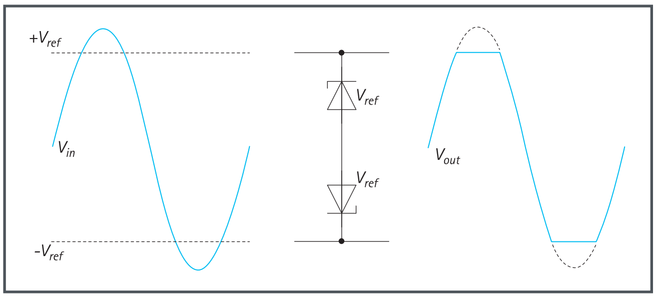


Figure B1.10:
Signal distortion due to excessive amplitude

in turn to the converter. The signals may be initially input to a number of simultaneous sample-and–hold circuits prior to multiplexing, or the time relationship between successive samples must be known if the phase relationship between signals is important. The alternative is to provide each input with a dedicated A/D converter, and logic to ensure that all converters perform the measurement simultaneously.

The frequency of sampling must be carefully considered, as the Nyquist criterion applies:

$$f_s \geq 2 \times f_h$$

where:

f_s = sampling frequency

f_h = highest frequency of interest

If too low a sampling frequency is chosen, aliasing of the input signal can occur (Figure B1.11), resulting in high frequencies appearing as part of signal in the frequency range of interest. Incorrect results will then be obtained. The solution is to apply an anti-aliasing filter, coupled with an appropriate choice of sampling frequency, to the analogue signal, so those frequency components that could cause aliasing are filtered out. Digital sine and cosine filters are used (Figure B1.12), with a frequency response shown in Figure B1.13, to extract the real and imaginary components of the signal.

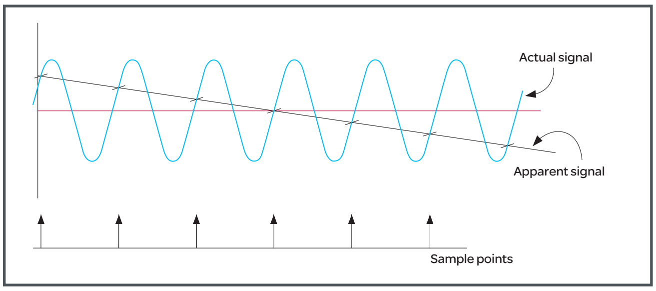


Figure B1.11:
Signal aliasing problem

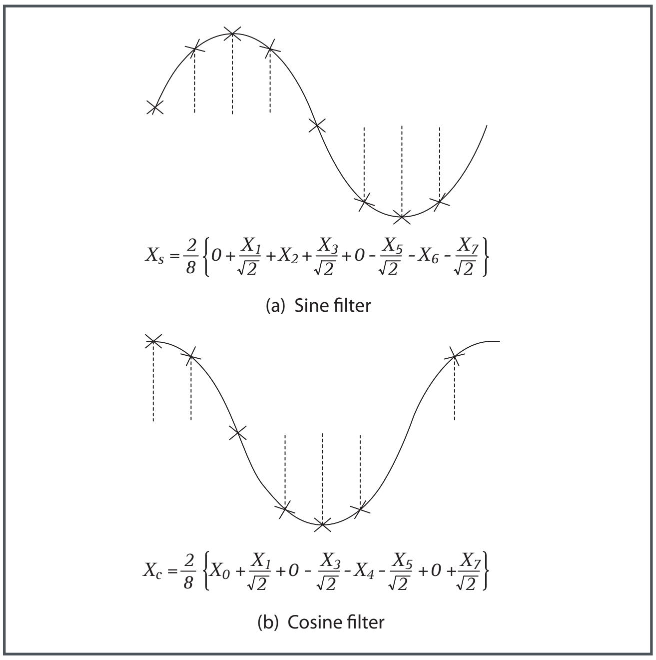


Figure B1.12:
Digital filters

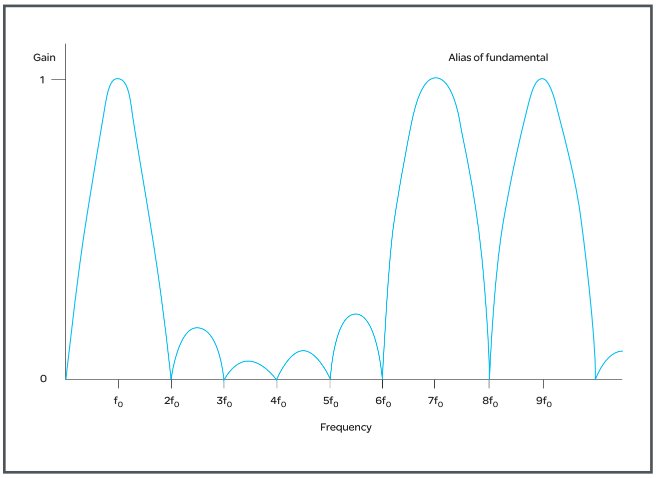


Figure B1.13:
Filter frequency response

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5. Numerical relays

Frequency tracking of the input signals is applied to adjust the sampling frequency so that the desired number of samples/cycle is always obtained. A modern numerical relay may sample each analogue input quantity at between 16 and 48 samples per cycle.

All subsequent signal processing is carried out digitally in software, final digital outputs use relays to provide isolation or are sent via an external communications bus to other devices.

5.2 Relay software

The software provided is commonly organised into a series of tasks, operating in real time. An essential component is the Real Time Operating System (RTOS), whose function is to ensure that the other tasks are executed as and when required, on a priority basis.

Other task software provided will naturally vary according to the function of the specific relay, but can be generalised as follows:

a. system services software – this is akin to the BIOS of an ordinary PC, and controls the low-level I/O for the relay (i.e. drivers for the relay hardware, boot-up sequence, etc.)

b. HMI interface software – the high level software for communicating with a user, via the front panel controls or through a data link to another computer running suitable software, storage of setting data, etc.

c. application software – this is the software that defines the protection function of the relay

d. auxiliary functions – software to implement other features offered in the relay – often structured as a series of modules to reflect the options offered to a user by the manufacturer

5.3 Application software

The relevant software algorithm is then applied. Firstly, the values of the quantities of interest have to be determined from the available information contained in the data samples. This is conveniently done by the application of the Discrete Fourier Transform (DFT), and the result is magnitude and phase information for the selected quantity. This calculation is repeated for all of the quantities of interest. The quantities can then be compared with the relay characteristic, and a decision made in terms of the following:

a. value above setting – start timers, etc.

b. timer expired – action alarm/trip

c. value returned below setting – reset timers, etc.

d. value below setting – do nothing

e. value still above setting – increment timer, etc.

Since the overall cycle time for the software is known, timers are generally implemented as counters.

6. Additional features of numerical relays

The processor in a numerical relay is normally of sufficient processing capacity that calculation of the relay protection function only occupies part of the processing capacity. The excess capacity is therefore available to perform other functions. Of course, care must be taken never to load the processor beyond capacity, for if this happens, the protection algorithm will not complete its calculation in the required time and the protection function will be compromised.

Typical functions that may be found in a numerical relay besides protection functions are described in this section. Note that not all functions may be found in a particular relay. In common with earlier generations of relays, manufacturers, in accordance with their perceived market segmentation, will offer different versions offering a different set of functions. Function parameters will generally be available for display on the front panel of the relay and also via an external communications port, but some by their nature may only be available at one output interface.

6.1 Measured values display

This is perhaps the most obvious and simple function to implement, as it involves the least additional processor time. The values that the relay must measure to perform its protection function have already been acquired and processed. It is therefore a simple task to display them on the front panel, and/or transmit as required to a remote computer/HMI station. Less obvious is that a number of extra quantities may be able to be derived from the measured quantities, depending on the input signals available. These might include:

a. sequence quantities (positive, negative, zero)

b. power, reactive power and power factor

c. energy (kWh, kvarh)

d. max. demand in a period (kW, kvar; average and peak values)

e. harmonic quantities

f. frequency

g. temperatures/RTD status

h. motor start information (start time, total no. of starts/ reaccelerations, total running time)

i. distance to fault

The accuracy of the measured values can only be as good as the accuracy of the transducers used (VTs CTs, A/D converter, etc.). As CTs and VTs for protection functions may have a different accuracy specification to those for metering functions, such data may not be sufficiently accurate for tariff purposes. However, it will be sufficiently accurate for an operator to assess system conditions and make appropriate decisions.

6.2 VT/CT supervision

If suitable VTs are used, supervision of the VT/CT supplies can be made available. VT supervision is made more complicated by the different conditions under which there may be no VT signal – some of which indicate VT failure and some occur because of a power system fault having occurred.

CT supervision is carried out more easily, the general principle being the calculation of a level of negative sequence current that is inconsistent with the calculated value of negative sequence voltage.

6.3 CB control/state indication/condition monitoring

System operators will normally require knowledge of the state of all circuit breakers under their control. The CB position-switch outputs can be connected to the relay digital inputs and hence provide the indication of state via the communications bus to a remote control centre.

Circuit breakers also require periodic maintenance of their operating mechanisms and contacts to ensure they will operate when required and that the fault capacity is not affected adversely. The requirement for maintenance is a function of the number of trip operations, the cumulative current broken and the type of breaker. A numerical relay can record all of these parameters and hence be configured to send an alarm when maintenance is due. If maintenance is not carried out within defined criteria (such as a pre-defined time or number of trips) after maintenance is required, the CB can be arranged to trip and lockout, or inhibit certain functions such as auto-reclose.

As the numerical relay is monitoring the state of the breaker it can also detect a failure of the breaker to open or close when requested. This information can then be used to alarm and to provide signals to other devices upstream to trip.

Finally, as well as tripping the CB as required under fault conditions, it can also be arranged for a digital output to be used for CB closure, so that separate CB close control circuits can be eliminated.

6.4 Disturbance recorder

The relay memory requires a certain minimum number of cycles of measured data to be stored for correct signal processing and detection of events. The memory can easily be expanded to allow storage of a greater time period of input data, both analogue and digital, plus the state of the relay outputs. It then has the capability to act as a disturbance recorder for the circuit being monitored, so that by freezing the memory at the instant of fault detection or trip, a record of the disturbance is available for later download and analysis. It may be inconvenient to download the record immediately, so facilities may be provided to capture and store a number of disturbances. In industrial and small distribution networks, this may be all that is required. In transmission networks, it may be necessary to provide a single recorder to monitor a number of circuits simultaneously, and in this case, a separate disturbance recorder will still be required.

6. Additional features of numerical relays

6.5 Time synchronisation

Disturbance records and data relating to energy consumption require time tagging to serve any useful purpose. Although an internal clock will normally be present, this is of limited accuracy and use of this clock to provide time information may cause problems if the disturbance record has to be correlated with similar records from other sources to obtain a complete picture of an event. Many numerical relays have the facility for time synchronisation from an external clock. The standard normally used is an IRIG-B signal, which may be derived from a number of sources, the latest being from a GPS satellite system.

6.6 Programmable logic

Logic functions are well suited to implementation using microprocessors. The implementation of logic in a relay is not new, as functions such as intertripping and auto-reclose require a certain amount of logic. However, by providing a substantial number of digital I/O and making the logic capable of being programmed using suitable off-line software, the functionality of such schemes can be enhanced and/or additional features provided. For instance, an overcurrent relay at the receiving end of a transformer feeder could use the temperature inputs provided to monitor transformer winding temperature and provide alarm/trip facilities to the operator/ upstream relay, eliminating the need for a separate winding temperature relay. This is an elementary example, but other advantages are evident to the relay manufacturer – different logic schemes required by different Utilities, etc., no longer need separate relay versions or some hard-wired logic to implement, reducing the cost of manufacture. It is also easier to customise a relay for a specific application and eliminate other devices that would otherwise be required.

6.7 Provision of setting groups

Historically, electromechanical and static relays have been provided with only one group of settings to be applied to the relay. Unfortunately, power systems change their topology due to operational reasons on a regular basis. (e.g. supply from normal/ emergency generation). The different configurations may require different relay settings to maintain the desired level of network protection (since, for the above example, the fault levels will be significantly different on parts of the network that remain energised under both conditions).

This problem can be overcome by the provision within the relay of a number of setting groups, only one of which is in use at any one time. Changeover between groups can be achieved from a remote command from the operator, or possibly through the programmable logic system. This may obviate the need for duplicate relays to be fitted with some form of switching arrangement of the inputs and outputs depending on network configuration. The operator will also have the ability to remotely program the relay with a group of settings if required.

6.8 Conclusions

The provision of extra facilities in numerical relays may avoid the need for other measurement/control devices to be fitted in a substation. A trend can therefore be discerned in which protection relays are provided with functionality that in the past has been provided using separate equipment. The protection relay no longer performs a basic protection function; but is becoming an integral and major part of a substation automation scheme. The choice of a protection relay rather than some other device is logical, as the protection relay is probably the only device that is virtually mandatory on circuits of any significant rating. Thus, the functions previously carried out by separate devices such as bay controllers, discrete metering transducers and similar devices are now found in a protection relay. It is now possible to implement a substation automation scheme using numerical relays as the principal or indeed only hardware provided at bay level. As the power of microprocessors continues to grow and pressure on operators to reduce costs continues, this trend will probably continue, one obvious development being the provision of RTU facilities in designated relays that act as local concentrators of information within the overall network automation scheme.

7. Numerical relay issues

The introduction of numerical relays replaces some of the issues of previous generations of relays with new ones. Some of the new issues that must be addressed are as follows:

a. software version control

b. relay data management

c. testing and commissioning

7.1 Software version control

Numerical relays perform their functions by means of software. The process used for software generation is no different in principle to that for any other device using real-time software, and includes the difficulties of developing code that is error-free. Manufacturers must therefore pay particular attention to the methodology used for software generation and testing to ensure that as far as possible, the code contains no errors. However, it is virtually impossible to perform internal tests that cover all possible combinations of external effects, etc., and therefore it must be accepted that errors may exist. In this respect, software used in relays is no different to any other software, where users accept that field use may uncover errors that may require changes to the software. Obviously, type testing can be expected to prove that the protection functions implemented by the relay are carried out properly, but it has been known for failures of rarely used auxiliary functions to occur under some conditions.

Where problems are discovered in software subsequent to the release of a numerical relay for sale, a new version of the software may be considered necessary. This process then requires some form of software version control to be implemented to keep track of:

a. the different software versions in existence

b. the differences between each version

c. the reasons for the change

d. relays fitted with each of the versions

With an effective version control system, manufacturers are able to advise users in the event of reported problems if the problem is a known software related problem and what remedial action is required. With the aid of suitable software held by a user, it may be possible to download the new software version instead of requiring a visit from a service engineer.

7.2 Relay data management

A numerical relay usually provides many more features than a relay using static or electromechanical technology. To use these features, the appropriate data must be entered into the memory of the relay. Users must also keep a record of all of the data, in case of data loss within the relay, or for use in system studies, etc. The amount of data per numerical relay may be 10-50 times that of an equivalent electromechanical relay, to which must be added the possibility of user-defined logic functions. The task of entering the data correctly into a numerical relay becomes a much more complex task than previously, which adds to the possibility of a mistake being made. Similarly, the amount of data that must be recorded is much larger, giving rise potentially to problems of storage.

The problems have been addressed by the provision of software to automate the preparation and download of relay setting data from a portable computer connected to a communications port of the relay. As part of the process, the setting data can be read back from the relay and compared with the desired settings to ensure that the download has been error-free. A copy of the setting data (including user defined logic schemes where used) can also be stored on the computer, for later printout and/or upload to the users database facilities.

More advanced software is available to perform the above functions from an Engineering Computer in a substation automation scheme.

7.3 Relay testing and commissioning

The testing of relays based on software is of necessity radically different from earlier generations of relays. The topic is dealt with in detail in Chapter "Relay Testing and Commissioning", but it can be mentioned here that site commissioning is usually restricted to the in-built software self-check and verification that currents and voltages measured by the relay are correct. Problems revealed by such tests require specialist equipment to resolve, and hence field policy is usually on a repair-by-replacement basis.