Abstract – The use of microprocessor based multifunction relays is on the increase due to the advantages they offer such as communications, measurements, simplified wiring, and reduced space requirements. Since many protection functions are included in one device however, there has been some concern about providing adequate protection should a multifunction relay fail. A reliable protection scheme is very important in order to protect capital equipment and operating personnel, and reduce down time by selectively clearing faults. This paper analyses some of the different means that have been used to achieve satisfactory levels of back-up protection using microprocessor based multifunction protection relays featuring the protection functions normally provided in large petrochemical plants.

Index Terms – protection relays, back-up protection, circuit-breaker, multifunction relay, microprocessor, electrical distribution

I. INTRODUCTION

This paper reviews the back-up protection features of an electrical distribution system typically found in a large petrochemical installation. After discussing the inherent back-up protection found in such systems, the authors show how certain features of microprocessor multifunction relays can be used to increase the reliability of the system and enhance the performance of the protection system as a whole.

A protection relay is part of the complete circuit required for the isolation of a section of an electrical distribution system. The protection circuit also includes a circuit-breaker with its trip coil, instrument transformers, auxiliary power supply, and control wiring. In addition to offering several protection functions in the same device, the typical microprocessor multifunction relay described in this paper also has a self monitoring function that is capable of detecting abnormal conditions within the complete protection circuit. The use of this feature to enhance back-up protection will be discussed.

For this paper the authors have assumed that microprocessor relays have been chosen for the application, and full use is made of the features they offer such as communication with higher level systems, self monitoring, and different sets of protection settings. The importance of related parameters such as the maximum earth fault current is also reviewed.

II. BASIC CONCEPTS

A. Redundancy versus Back-up Protection

The purpose of protection relays is to detect a fault and give a trip order to the switching device that is closest to the fault location. A fault in a motor feeder will generally result in the non-availability of the motor and should it be critical for the process, only the use of a standby motor will allow production to continue. Fig. 1 shows an electrical distribution system typical of large petrochemical plants (please refer to Fig. 22 at the end of the paper for a list of all the symbols used). Switchboards are normally double ended which means that the loss of a transformer supplying one of the busbars will not result in a loss of supply since the other transformer generally has sufficient capacity to supply both busbars. From a process point of view it is necessary to have redundant motors and transformers as shown to ensure continued production. Correct operation of the protection circuit including back-up protection may ensure optimal clearance of the fault but will not in itself prevent a loss of production. In other words good back-up protection will not fix a bad design.

Generally the redundancy in petrochemical plants is designed based on the occurrence of single events such as the loss of one transformer or one drive. The philosophy of back-up protection goes one step further since it is based on the simultaneous occurrence of two failures: an electrical fault AND a protection circuit fault. A typical example is breaker-failure protection that trips all surrounding circuit-breakers should a fault occur AND the circuit-breaker not open as required.

B. Unit and Time graded Protection Systems

For protection purposes, the power system is often divided into zones such that no part is left unprotected. A selective protection system ensures that only the circuit-breakers nearest the fault will trip thereby limiting the effects on the healthy part of the system. There are two basic methods used, unit protection and time graded protection. Back-up
protection concepts are very different for both of these methods.

In unit protection the currents at the boundary of the zone are compared. A typical example of this is busbar differential protection. Unit protection is inherently very fast since it is possible to determine whether or not the fault is within the zone and if so initiate immediate tripping of the protective devices. Any fault occurring outside the zone will not be detected however, which means that unit protection does not have an inherent back-up feature. Back-up protection for a particular zone will therefore require additional equipment, or it must be included in a larger zone.

The time graded method is based on the fault current flowing through adjacent zones and thus being detected by several protection relays. If the relays are correctly set, the circuit-breaker closest to the fault will be tripped before those in upstream zones have time to operate. Back-up protection is therefore inherent with this method. This inherent back-up protection will not eliminate the fault quickly however, and this could result in damage to equipment or loss of system stability. Different means of reducing the tripping time will be presented later in the paper.

The position of the bus-tie current transformers shown for the 33kV partial differential protection is one of the solutions commonly used. It is important that the position of all instrument transformers be reviewed during the design phase.

C. Typical Microprocessor Based Multifunction Relays

Fig. 2 shows the complete protection circuit, which includes the multifunction protection relay, a circuit-breaker, instrument transformers, and an auxiliary power supply.

![Diagram of complete protection circuit](fig2)

The architecture of a typical microprocessor multifunction relay is illustrated in Fig. 3. State of the art relays have continuous self monitoring which controls watchdog contacts that change state should there be an internal failure. Although the self monitoring will find most failures, some such as a disconnected sensitive earth fault toroidal current transformer may not be detected.

![Diagram of typical microprocessor multifunction relay](fig3)

D. Correct Use of Self Monitoring in Microprocessor Devices

As mentioned above, self monitoring is capable of detecting most internal failures in protection circuits. The watchdog contacts should therefore be connected to the higher level system to generate an alarm and to give precise information to what relay is defective. The maintenance staff should repair the faulty device without delay and this is often enough to prevent damage to equipment and loss of production. The watchdog contacts can also be used to provide back-up protection by other relays and to change protection settings.
of upstream relays as will be described later in the paper. All microprocessor relays are not created equal and these features should be carefully reviewed when selecting relays and the appropriate back-up protection scheme.

The watchdog relay coil is normally kept energized by the self monitoring function. Care must be taken in using these contacts to prevent nuisance trips. For example a watchdog contact used to change settings of another relay should be wired in series with an auxiliary contact of its circuit-breaker to block the changes if the circuit-breaker is open.

E. Design and Commissioning

For the purposes of this paper we assume that:

1) there are no design errors
2) the protection settings are correct
3) the commissioning has been done correctly

The authors’ experience and reference [1] show that very often the reason for extensive damage in installations is not the fault of the protection equipment but how it was implemented. The best back-up protection scheme is of no use if the equipment is incorrectly wired and the relays incorrectly set. Before deciding to add additional equipment in existing installations, it is recommended to thoroughly check what has already been installed to ensure that it is connected properly and that the protection settings are correct. Adding equipment makes circuits more complicated and therefore harder to operate and maintain.

III. EFFECT OF DOUBLING RELAYS ON AVAILABILITY

One point that is sometimes raised when applying microprocessor based protection relays is that all protection functions are in the same device. Often doubling the protection relay is given as a solution. Since the protection relay is only a part of the protection circuit we decided to compare the availability of 2 motor feeders, one feeder using a single microprocessor relay, the other having 2 identical microprocessor relays, each with its associated auxiliary supply and circuit-breaker trip coil as shown in Fig. 4. In both cases there is only one set of current transformers, and one circuit-breaker in the protection circuit. For the availability comparison we considered the following undesirable events for both circuits:

Event 1: The busbar is deenergized.
Event 2: The motor is deenergized.

Event 1 can occur if there is an insulation failure in the circuit-breaker itself, or if there is simultaneously a failure of the protection circuit AND an electrical fault in the motor feeder. The fault is eliminated by the supply side circuit-breaker. Event 2 can occur if there is an electrical fault in the motor feeder or due to a nuisance trip from the protection relay. The failure rates and mean time to repair data for the calculations were obtained from the IEEE Yellow Book for the circuit-breaker, current transformers, cable etc. and from manufacturer’s data for the microprocessor based protection relays. The results for both events are summarized below:

1. Event 1: The principal cause for a deenergization of the busbar is an insulation fault of the circuit-breaker. The failure of a relay does not have a significant impact on this since it must be coupled with an electrical failure to cause the incoming circuit-breaker to trip. This is very unlikely since most of the possible causes for protection relay failure will be detected by the self monitoring feature thereby reducing the time period when an electrical fault will have to be eliminated by the supply side circuit-breaker.

2. Event 2: Adding a second relay will double the risk of a nuisance trip. Since the calculations also take into account electrical faults on the motor feeder circuit which have a much higher impact on the availability, the addition of a second relay does not result in a significant change in the availability of the motor.

This simple comparison shows that adding extra relays will not have a significant effect on the availability of the electrical distribution system provided that the self monitoring features of the microprocessor relay are correctly implemented. In addition, although not considered in the analysis, there is an increased risk of incorrect implementation of more complex schemes, and as pointed out in [2] maltrips are often not fully random, but more likely to occur when the system is faulted. This tends to increase the possibility that both protection relays will fail during a fault condition even though this is not taken into account in our simulations. Doubling the protection relays should not be the immediate and only answer to the question “Is my protection system sufficiently reliable?” As is demonstrated in the following sections of the paper there are other means of enhancing reliability that should be considered before adding additional equipment.

IV. TYPICAL PETROCHEMICAL PLANT DISTRIBUTION SYSTEM

The electrical distribution system and protection functions shown in Fig. 1 are typical of a large petrochemical plant. Examples of switchboards having both the tie normally open and normally closed are discussed since both are often used. The single-line diagram used for discussion is based on medium-voltage distribution only. The reason for this choice is that:

- High voltage connections are often subject to utility protection requirements and the user has little choice in protection. For plants where this is not the case, the
discussion related to the 33kV switchgear can be applied.

- Microprocessor relays are more frequently used in high voltage than low voltage although this trend is changing.

In Fig. 1 all circuit-breakers are normally closed except for the bus-tie of the 6.6kV switchboard. All protection functions included in the same rectangle are implemented by the same microprocessor protection relay. When the relay has an internal fault none of the protection functions will operate. Breaker failure protection (50BF) is not shown on the single line diagram since it is not commonly used for medium voltage distribution. Since multifunction relays can often provide this function we recommend its use. This can reduce the time required for upstream circuit-breakers to clear faults thereby reducing damage to equipment.

For each analysis protection curves are used to illustrate the back-up protection features. For ease of reading we have used a time margin of 300ms and an operating time of 100ms for instantaneous protection. The time margin used for a particular application will depend on the circuit-breaker operating time, the type of protection relay, and the characteristics of the chosen curves.

V. ANALYSIS OF DISTRIBUTION SYSTEM BACK-UP PROTECTION

The back-up protection features implemented in the single line diagram will be reviewed for different parts of the circuit. For each case we will present methods such that the back-up protection can be improved, often without adding additional equipment or functions. The analysis will consider both protection circuit faults detected by the self monitoring function of the relay, and other faults such as breaker failure. Except for the transformer circuit, the analyses are based only on phase-to-phase faults. The same type of reasoning can however be applied to earth faults.

A. Motor Feeder

Fig. 5 shows a 6.6kV motor on bus A being supplied from the incoming of bus B via the tie circuit. Fig. 6 shows the fault clearing times of the all of the 6.6kV relays. Since time graded protection is used, inherent back up is provided as illustrated by Fig. 6. The disadvantage of this scheme is the long time needed to clear a fault occurring on bus B (about 700ms) even when the motor is supplied from bus A, which is the normal configuration shown in Fig. 1. Since microprocessor based relays often have multiple protection curves, it is very easy to reduce the time delay of the incoming protection relay when the tie is open (normal operating configuration). An auxiliary contact of the tie breaker is wired to an input of the relay of each incoming circuit. When the tie is open the relay of each incoming circuit will automatically use the lower settings as shown in Fig. 7. Since this is the standard operating condition these will be the fault clearing times normally used and will still guarantee selective tripping and back-up protection.

The next improvement that can be easily implemented is shown in Fig. 8. The watchdog contact is shown in each feeder relay (F1, F2 and F3). This contact is open when the relay is energized and no internal faults have been detected, which is the case for relay F2. Relay F1 has an internal fault resulting in a closed watchdog contact. Each watchdog contact is connected directly to the trip coil of the associated circuit-breaker. In order to prevent nuisance operations when a feeder has been deenergized such as for F3, an auxiliary contact of the associated circuit-breaker is wired in series with the watchdog contact.
In addition to the normal output connected to the trip coil of its associated circuit-breaker, the relay F4 of the incomer has a separate output which closes instantaneously should fault current be detected. Should a fault occur in the circuit which has a faulty relay such as F1 in this example, the separate output contact of relay F4 will be connected via the watchdog contact of relay F1 to the circuit-breaker trip coil and will open the circuit-breaker immediately, thus providing back-up protection. The curves associated with this back-up protection are shown in Fig. 9. The authors recommend use of this simple and effective system for all switchboards.

Both the inherent and improved back-up protection described above are effective for earth and phase faults but do not provide any back-up protection for overload conditions. When a relay has an internal fault the operators should immediately switch to the standby motor and proceed with replacement of the relay without delay. If a standby motor is not available and there is a risk of overloading the motor during the time required to replace the faulty relay, addition of a simple overload relay for additional back-up protection should be considered.

### B. Prevention of Unauthorized Transfers

Fig. 10 shows the intertrip signals often associated with an automatic transfer scheme (ATS). The logic for the transfer scheme can be performed in the multifunction relay F1 of the incoming circuit. In such cases a malfunction of F1 will not result in an unauthorized transfer since the transfer logic will not be operational. For cases where the logic is performed outside of F1 as shown in Fig. 10 consideration should be given to what happens should the incomer relay F1 have a fault condition (detected by self monitoring or not). Correct
operation requires F1 to block the transfer for uncleared faults that occur downstream of the incoming circuit-breaker QT1S. Should a short circuit occur on the 6.6kV bus (earth faults are discussed in the following section) and F1 be out of service, the upstream relay F2 will detect the fault, trip QT1P, intertrip QT1S, and initiate the automatic transfer. F1, being out of service, will not deliver the required blocking signal to the ATS and this could result in closing the tie breaker to the 6.6kV bus fault. In order to prevent such incorrect operations from occurring, we recommend that all signals to trip QT1S transit relay F1 as shown in Fig. 10. The automatic transfer logic cannot close the tie breaker until the incoming breaker QT1S is open. Having the trip signal from the ATS as well as the intertrip from the upstream circuit-breaker transit F1 as shown, will prevent QT1S from opening should F1 be faulty, thus effectively blocking any incorrect transfer. Intertrips to upstream circuit-breakers should be direct (e.g. QT1S to QT1P) in order to prevent relay faults from inhibiting opening a circuit-breaker.

C. Earth Fault Protection

Fig. 10 also shows that there is no earth fault back-up protection for QT1S since both the 51N and 51G functions are in F1. We recommend that the upstream relay F2 have a 51G function as shown in Fig. 11. Back-up protection will now be provided for all parts of the 6.6 kV system. The earth fault protection curves are shown in Fig. 12. As will be discussed in the next section, should a fault condition be detected in a relay by self monitoring, the earth fault time delay settings can be reduced to allow quicker fault elimination.

D. Transformer Protection

For the following discussion about transformer protection, we will first consider measures that can be taken to enhance back-up protection for the circuit of Fig. 11. Fig. 13 shows the standard transformer protection settings for the phase protection. Since time graded protection is used back-up protection is inherent in this scheme. The first improvement that can be implemented very easily is the changing of settings of F2 should an internal fault be detected in F1. Fig. 14 shows the reduction of the tripping times when this simple measure is implemented. The inverse time portion of the modified curve of F2 provides satisfactory back-up overload protection even though it is not as effective as the thermostat. Should an internal fault be detected in F2, the 33kV bus A incoming relay can be used as a back up as discussed previously in the section on motors.
For large power transformers it is very common to use transformer differential protection (87T) as primary protection as shown in Fig 15. The use of this relay is an example of unit protection described in the first section of the paper. It will also provide quicker tripping for faults located on the transformer secondary, upstream of the incoming circuit-breaker. As is the case for unit protection in general, the 87T will not provide any overload protection. Overload protection as well as back-up protection will be provided by F2. Transformer differential protection is often combined with restricted earth fault protection (87REF), once again allowing easier understanding of the discussion, relays F1 and F2 are both shown as having two different sets of protection functions: one set is specific for the incoming circuit (67, 67N, 51, 51N), and the other set (51, 51N) is for the partial differential circuit consisting of the incoming and bus-tie current transformers connected in parallel. The protection curves for these functions are shown in Fig. 17. Since the partial differential protection is selective only with respect to outgoing feeders, busbar faults are cleared relatively quickly as shown. Care must be taken when defining the tripping matrix for the relays. Directional protection should trip only the incoming circuit-breaker whereas the other protection functions should trip both the incoming and the bus-tie circuit-breakers.

Fig. 14. Automatic lowering of upstream protection settings

Fig. 15. Differential and restricted earth fault protection for quicker fault clearance typical of unit protection.

E.  Incoming 33kV Main-Tie-Main with Tie Normally Closed

Fig. 16 shows the protection functions of double-ended switchgear operating with the bus-tie normally closed. For
protection as shown in Fig. 18. The busbar differential protection becomes the primary protection and is backed up by the other relays. The relay on the bus-tie will also provide back-up protection for the incoming relay for upstream faults.

The failure of the bus-tie circuit-breaker to open will probably result in total loss of power since it is common to both busbars. Should a fault in the bus-tie protection circuit be detected by self monitoring, the bus-tie circuit-breaker should be immediately tripped by the watchdog contact of the bus-tie relay in order to isolate each busbar and limit the influence of faults to only one busbar section.

VI. EARTH FAULT CURRENT LIMITATION

In order to prevent damage to rotating equipment the magnitude and duration of earth fault current should be kept within acceptable limits as defined by manufacturers' damage curves. Fig. 19 gives a typical set of damage curves for medium voltage motors and shows the 3 regions where there is negligible, slight, and severe damage. The curves show that earth fault current should be limited to less than about 50A assuming that earth fault protection will operate with a minimum time delay (this is normally the case for motor feeders). In order to provide proper protection for the windings, the earth fault protection should be set at approximately 10% of the maximum earth fault current (5A in this case). Reliable measurement of these low values of earth fault current can be achieved with core balance current transformers shown on the motor feeder circuits.

There are however, other technical reasons for having higher values of earth fault current. One reason is that in many cases core balance current transformers cannot be used (bus-tie circuit), and the earth fault current is measured by means of residually connected current transformers (CT) as shown in Fig. 20. Due to tolerances in the CTs, reliable measurements can be made down to about 10% of the rated CT current. For example, earth fault protection for a circuit having residually connected CTs rated 2500A/5A would be possible only if the maximum earth fault current exceeded 250A (10% of 2500A). Another reason is that the earth fault current should be at least twice the value of the cable charging current. Distribution systems with long lengths of cable will therefore require high values of earth fault current.

Care must be taken in choosing the right value for earth fault current. Too low a value may result in non-operation of some protection relays or overvoltages, whereas too high a value may result in severe damage to rotating machines. The protection engineer should participate in the decision in order to ensure that he will be able to set the relays correctly.

VII. REDUCTION OF TRIP TIMES

Many projects today require medium voltage switchgear that can withstand the effects of internal arcs. Annex AA of IEC standard 60298 specifies the test requirements for such gear and allows the duration of the test to be less than the duration of the short-time withstand current assuming that internal faults will be cleared very quickly. Time graded protection cannot provide both quick fault clearance and...
protection grading. In order to achieve the fault clearance times compatible with arc resistant switchgear, unit protection such as busbar protection is often used as previously discussed. Another method that does not require an additional protection relay or additional current transformers is logic selectivity as shown in Fig. 21. In this scheme a downstream relay F1 which detects a fault will send a signal to the upstream relay F2 to wait during the time required to eliminate the fault. Should the upstream relay detect a fault and not receive a signal to wait, it will trip its circuit-breaker immediately. Tripping times similar to those obtained with unit protection can be achieved and are compatible with the arc withstand duration. Logic selectivity is available in many multifunction relays.

VIII. RECOMMENDATIONS FOR PROTECTION RELAYS

As can be seen from the analyses, multifunction protection relays should have following features:

1. Allow quick replacement (i.e. without disconnecting control wiring).
2. The replacement relay must be quickly configurable with the same configuration as the replaced relay.
3. The self monitoring should detect most internal faults, as well as breaker trip coil faults.
4. The relay must have successfully passed all EMC tests to ensure correct operation.

IX. REQUIREMENTS FOR DESIGN

For correct operation of the protection system, the design should take into account the following points:

1. Continuous operation should not depend on one circuit or one busbar only. Ensure that maintenance can be carried out without total deenergization of the plant.
2. Make sure you can live with what happens when back-up protection operates. If not then the design of the electrical distribution system is not correct.
3. Microprocessor multifunction relays from different manufacturers often have very different characteristics. Review all features when selecting a relay.
4. Make use of other relays when present to enhance back-up protection. Adding extra components will often decrease reliability due to the difficulty of correctly designing and maintaining more complicated systems.
5. Choose the maximum earth fault current carefully as it has an impact on both earth-fault and unit protection.
6. When intertripping is performed, the relay should send the trip order directly to the other breaker and not through the related relay. This is more reliable for clearing faults. The one exception is for intertripping in the case of automatic transfer to prevent disastrous closing to a faulted bus.

X. CONCLUSION

The protection scheme typically found in the electrical distribution system of petrochemical plants has a certain level of inherent back-up protection. This can be easily enhanced by the correct use of the self monitoring function of multifunction microprocessor based relays. Back-up protection can often be improved without adding additional protection functions or relays by using available functions of existing relays as shown for motor feeders. Since certain features of multifunction relays from different manufacturers will not be the same, their influence on the performance of back-up protection should be reviewed very early in the design phase in order to obtain the best combination of protection and continuous operation. Any analysis of back-up protection must look at the complete protection circuit consisting of the circuit-breaker, the instrument transformers, the auxiliary power supply, and the relay. Just adding additional relays will probably do more harm than good. As Mark Twain said, "It's ok to put all your eggs in one basket, but watch that basket!"

XI. REFERENCES

XII. VITAS

Terry Hazel graduated from the University of Manitoba Canada with a BScEE in 1970. He worked for one year as a power coordination engineer in Perth Australia and for several years in Frankfurt Germany as a consulting engineer for construction and renovation of industrial power distribution systems. Since 1980 he has worked for Schneider Electric (formerly Merlin Gerin) in their projects group where he has provided team leadership for several major international projects involving process control and power distribution. His main interests are in power quality, and the reliability of electrical distribution systems. Mr. Hazel is a senior member of IEEE and is author of a PCIC paper and tutorial.

Jacques Tastet graduated from the EEIP School in France with an Engineering Degree in 1974. He worked for one year for the French EdF Distribution Board in the power distribution branch. He joined the electrical Department of Technip in 1976 where he has provided team leadership for several major international oil & gas projects involving power generation and distribution. For the last 6 years, he has been the Head of Technip France electrical Department. His main interests are in power reliability, providing continuity of service and safety in major petrochemical complexes such as refineries. Mr. Tastet participates in European conferences concerning centralized control and the safety of electrical distribution systems.

Noël Quillion received his degree from the Electrical Engineering Institute, Grenoble, France in 1977. Following graduation he worked for several years with Schneider Electric (formerly Merlin Gerin) as a power system analysis specialist and provided training for both employees and customers. Since 1991 he is with their protection and control systems department designing and implementing protection schemes for industrial applications.

Bruno Lusson graduated in 1989 from the Lille Engineering School in France. Prior to 1994 he worked with Jeumont Schneider in the power electronics branch dealing with high power variable speed drives and rectifiers for aluminum smelters and electric arc furnaces. He is now with Schneider Electric and is a power system analysis specialist interested particularly in power quality issues and system reliability.