ELECTRONIC PROTECTION PACKAGES AND THEIR EFFECT ON POWER SYSTEM AVAILABILITY

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I. INTRODUCTION

Due to increasing electrical energy concentration and the related complexity of generation and transmission networks the question of availability and reliability of electrical service is receiving considerable attention from the power system engineers. Qualitative and quantitative reliability analyses of power outages caused by the failure or misoperation of various equipments have been made.

Protection systems have a very important effect on the reliability and availability of a power system since they act directly and automatically on the circuit breakers which control the power flow. The necessary standard of reliability is therefore very high, and the performance requirements for the protective systems are becoming very severe and varied.

To meet these demands, and at the same time retain the economic justification, (investment-damage risk analysis) the protective systems are being designed using a modular package concept approach.

2. RELIABILITY CONSIDERATIONS

Basically the relaying equipment is designed to operate so that the damage, the losses due to interruption of power flow and the danger to personnel and material resulting from a fault in the protected equipment is kept to a minimum. These design parameters are affected by the nature of the fault, the size and importance of the protected object and the probable number of faults within the period under consideration. In addition, the protective

systems, acting together with automatic control logic, also contribute extensively to reduce the transient forced outages (1) to an optimal minimum. Hence, a highly reliable protective scheme can effectively increase the availability index of electrical service.

The reliability of a protection system depends largely upon its:

--dependability
--security and
--selectivity

To evaluate the reliability it is therefore not sufficient to analyze the performance of individual relays; one must also consider the design of the entire protective system. The probability of occurrence of marginal conditions where the operating limits of the relaying scheme may be reached must also be taken into account (back-up protection schemes) in evaluating the effect which protective schemes have on the power supply availability.

The reliability of a protective scheme depends basically on the following factors:

-- The average period of selective operation of the protective scheme without failure, defined as the mean time between failure (MTBF (1), expressed as the reciprocal value of the mathematical probability index (e.g., annual rate of failures).

-- The period of permanent forced outages expressed as a product of the number of expected failures and the average time required to affect repairs (MTTR).

-- The scheduled outages necessary to do routine and special maintenance, make modifications, etc. expressed as mean time to do maintenance (MTM).

From the above the index of availability of the protective system can be defined as the ratio of:

$$\frac{\text{MTBF}}{\text{MTBF} + (\text{MTTR} + \text{MTM})}$$

The availability of a protective system can therefore be increased by measures that:

-- reduce the mean time to repair and that of routine maintenance (MTTR + MTM) and

-- increase the probable operating time without developing a defect (longer MTBF).

Each part to be protected presents an individual problem depending on its own design and duty. A cable, an over-head line within a city, or a cross country transmission line each require a different protective relay system. Other examples are reclosing in connection with parallel lines in the same system and reclosing on tie-lines inter-connecting two separate systems. The protective system required for a generator also varies considerably depend-ing on it's size, type and use. The overall power system configuration also has a direct effect on the protective relays. The number and types of relays available is therefore quite considerable. With the introduction of solid state relays on a modular basis it became feasible to coordinate and to combine the protective system with the control, regulation and communications equipment. The individual modules plug in to PC-card enclosures which can be installed in standard 19" racks or in special cabinets. The extreme flexibility offered by this system is obvious.

It is now possible to combine a number of basic elements to realize a nearly unlimited number of variations thus adapting the protective scheme to meet the individual requirements. Additional advantages are ease of commiss-ioning, servicing and stocking of spare parts.

The design of electronic relays on a modular basis also improves the availability of the protective system. Since the relays are designed on a withdrawable basis, a spare module can be plugged in to replace a faulty module which can then be repaired at leisure. This leads to an import-ant reduction in the mean time to repair and consequently increases the availability index by reducing the forced outage time.

The contribution resulting from the scheduled outage necessary to do routine maintenance can be made minimal by scheduling the outages to coincide with those of the protected elements as far as possible. This is only possible if the average period of operation without need for routine or special maintenance can be made to exceed the corresponding period for the primary elements of the system. This condition can be met quite easily by elec-tronic relays designed on a modular basis.

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Improvement of the mean time between failure figures

Thanks to the sensitivity of the electronic components and their design flexibility, electronic relays are inherently more sensitive than their corresponding electro-mechanical equivalents. In addition they can be designed so that the characteristics of the relay are better matched to the system requirements. Where the speed can be taken advantage of, the faster response of the electronic relays reduces the damage to the protected equipment. The relatively small power consumption of the electronic relays imposes less severe conditions on the instrument transformers. Thus, they tend to reduce the duration of transient forced outages of the system through faster fault clearance and subsequent automatic reclosure wherever possible. The sensitivity of the electronic components also permits us to design the relays with a very large safety margin between the sensitivity and the rated service level. The effect of external interference factors, such as induced voltage spikes, is eliminated within the electronic relay by such techniques as galvanic separation of the input and the relay quantities, capacitive shielding, filters, introduction of artificial time delays at each step, and by using integration instead of impulse techniques. These precautions contribute to a reduction in the failure rate of electronic relays due to faulty components.

The reliability performance figures can be improved considerably by applying self-monitoring techniques (2). Supervision of the various relay signals at different stages of evaluation of the fault conditions in an anti-valence logic circuit reduces the probability of non-selective operation between two scheduled outages for maintenance purposes, and increases the mean time between failure rate (9).

The time needed for routine testing (MTM) can be minimized by simplifying the testing procedures, for instance by using push button logic to test the performance of the equipment. As a further step, integrated automatic testing procedures incorporated in the relaying equipment reduce the testing time considerably thereby decreasing the time of non-availability.

It is clear from the above that an optimum solution for electronic protective systems from the point of view of availability can be achieved by combining all the modules of a particular protective scheme in a single package. This also keeps the inter-module wiring as short as possible. The self supervision and testing circuits to be incorporated become simple and the cost of the package is optimized without adversely affecting the reliability.

The design of such prefabricated and factory pretested package units reduces the design work load on the power system protection engineers. This has another advantage in that the installation and commissioning time are reduced to a minimum.

In what follows a few of the typical electronic relay packages incorporating the above considerations for the protection of different equipments are presented.

3. TYPICAL EXAMPLES OF ELECTRONIC RELAY PACKAGES

Generator protection

Fig. 1 shows a typical generator protection package which was presented at this conference last year (3). The principle of duplication of protective functions with different relays, division of the relay modules into two completely separate groups from the dc/dc converter right down to the tripping contactors, the possibility of testing one of these groups while keeping the other in service, quantitative testing using secondary injection method, etc. not only increase the reliability of the protective equipment, but also help to increase the availability of the protected generator.

Fig. 2 shows an automatic testing unit which can be added to the generator protection package. With this equipment each module in the generator protective relaying scheme can be tested quantitatively at periodic time intervals. The automatic testing equipment injects the current, voltage and other necessary quantities at the input of the relays, thereby checking the complete protective system including the intermodule wiring. Provision has also been made to compare the set value with the pick-up level. Each time the test is made, a hard copy print-out is made available indicating both the set and the

actual pick-up values. This arrangement enables the power system engineer to continuously supervise the individual relays and take the necessary preventive measures before any non-selective tripping can occur. Nearly all faults in the generator are detected by at least two relays and therefore protection to the machine is continuous even when one group of relays is being tested. Thus a back-up protection is assured without actual duplication of the material. A special module compares the tripping commands with the current in the trip circuit of the circuit breaker thus enabling the supervision of the tripping channel. This information is used to provide breaker failure back-up protection; if the tripping command is not carried out, the back-up functions for a failed breaker are automatically initiated by the protection package. Thus it can be seen that the generator protection package, supplemented with the automatic testing equipment and the matrix facilities goes a very long way in reducing the mean time to repair and the outages for maintenance as well as in increasing the MTBF. The net effect of this is an increased availability index for the generator.

Each relay module as well as the basic protection package, including the testing facilities, is prefabricated and pretested at the factory. These can be combined in a very simple way thus reducing the planning costs to a minimum. The compact design of the protective system, supplemented by the supervisory facilities mentioned above increases the security against false tripping to a maximum.

Line Protection

For the protection of extra high voltage lines from about 220 kV upwards, static distance relays have been in use for many years. Fig. 3 shows a view of this protection package which is described in reference (4). As can be seen the individual relay functions such as zone 1, zone 2 and zone 3 relaying, low set overcurrent supervision, line pick-up features, automatic reclosing facilities, HF interface modules etc., are combined to form a complete relay package system. This packaging makes it possible to introduce selfmonitoring facilities such as the supervision of the zone 1 and 2 relaying by zone 3 relaying, as well as the low set overcurrent relays. In the application of this distance relaying scheme for special purposes, such as to protect transmission lines equipped with series capacitors with a very high degree of compensation, the same modules can be combined to assure optimum protection. Fig. 4 shows one typical package. A description of the protection scheme appears in reference (5,6,7). The basic design philosophy

in the design of this scheme is that a failure of any single component of the protection system shall not cause nonselective operation, nor shall the relay fail to operate correctly. To achieve this performance it was necessary to provide a double set of relays, each consisting of one set of zone 3 relays (6 measuring elements) and 2 sets of zone 1 and 2 measuring elements each operating off a separate measuring quantity. By combining the directional comparison with overreach as well as with the step acceleration scheme, it was possible to achieve optimum and reliable performance of the relaying scheme under the most severe conditions, such as asymmetrical gap flashover during single phase or two phase faults. Each scheme is provided with two power supplies and two sets of tripping devices. For security reasons the carrier relaying channel linking the two ends of the protected line is also duplicated (6,7).

Thus by using the modular construction approach, such an extensive scheme meeting the specific requirements and problems was assembled without requiring design of new elements.

Fig. 5 shows another static distance relay (3) for application in medium and high voltage networks. This distance relay is normally equipped with an overcurrent starting element and is used in a simple scheme. The basic unit of this element is accommodated in one chassis; and the power supply units as well as the additional parts such as the impedance starting elements or voltage dependent overcurrent starting elements, HF interface, pilot wire interface, etc., can be located in a second chassis. Facilities to select the polarizing voltages for the measuring elements as necessary are also provided.

To assist the project engineer in selecting the individual modules to be combined, there are selection tables available showing the preferred combination for most normal conditions. This package incorporates the selfmonitoring technique in that the zone 3 element output, fault current detectors, timers, zone 1 and 2 output signals, auxiliary voltage etc. are monitored continuously by an antivalence logic circuit. A tripping command can occur only in case of logical coincidence of the different signals. In case of non-agreement provision can be made to block the relay and signal a "relay failure" alarm (9).

System decoupling device

Small industrial plant generators operating in parallel with a large interconnected system require a high speed decoupling device to maintain their stability (8). Due to the extreme difference in the inertia of the two systems, the generator could fall out of step if not decoupled from the system if a fault occurs in the supply system, and the power to the essential auxiliaries of the system would be lost. The decoupling device (fig. 6) monitors the voltage, the frequency and the direction of the current in the incoming lines. A combination of underfrequency coupled with the current direction in the network, and with low voltage, can be used to initiate the decoupling. In addition, the multistep frequency relay can be used for load shedding after a decoupling operation. Thus the availability of the power supply to essential auxiliaries of the industrial plant is maintained.

Busbar protection and breaker back-up protection

Fig. 7 shows a static selective busbar protection system. This protection scheme has been specifically tailored to the needs of protecting very important, complex busbar systems. Whereas in the case of line protection the design always tends towards overfunctioning by using one out of two systems, etc. (OR-function) the importance of the busbar protection requires a very high standard of reliability and security for the protective systems (9). Non-selective tripping cannot be tolerated since the loss of a node point can mean a sizeable reduction in the availability index of the power system. For this reason the bus protection system as a whole is normally not duplicated. At least two different criteria in a "series" connection (AND-function) must be met before tripping can occur. The two criteria are also completely different from each other, as for example the level of the differential current and the direction of the currents feeding the fault. This has the advantage of making the bus protection schemes almost independent of c.t. saturation. In addition to the normal supervisory functions such as monitoring of the secondary current transformer leads, supervision of auxiliary contacts where necessary, supervision of the auxiliary voltage of the protective system, logical comparison of the level of the differential current as well as the directional comparison criteria, etc., a special automatic testing equipment

is also included. This reduces the probability of failure between scheduled maintenance outages. The testing can be initiated automatically by a clock at periodic intervals, manually, or by remote control. The entire testing procedure takes about three to four seconds and simulates faults within and outside the protected zone for each feeder connected to the bus section. If a fault is detected in one of the elements an alarm sounds and the protection can be blocked. By noting the step at which the testing procedure was interrupted, and the signal lamp indications in the busbar cubicle, the faulty module is easily identified and replaced. Such a replacement can thus be undertaken even by non-skilled personnel without losing much time to locate the fault.

Due to the modular concept it is possible to build up a bus protection suitable to the configuration of any bus system simply by specifying the required number of identical modules. An advantage of this system is the ease and simplicity with which the protection scheme can be extended to accommodate future changes.

The operating experience with this type of automatic testing equipment over the past ten years has been very positive. It is interesting to note that at the beginning when this equipment was first put into service the automatic testing was done daily. Based on the excellent experience gained and the resulting increase in customer confidence, the automatic testing is now being performed once a week only at the request of the protection system engineers.

On the 300 busbar protection systems now in service, at least 5 component failures have been detected to our knowledge by the automatic testing feature before a non-selective tripping could occur.

The element which normally is not duplicated in the chain of the automatic fault elimination system is the circuit breakers. Therefore a breaker failure back-up protection consisting of a low set current detector which has a very rapid fall back time, together with the protective relaying schemes is used. The operation of the protective relaying and the low set current detector, starts a timer. If the relay has not fallen back after a preset time, the trip command is given either to the second trip coil of the circuit breaker, or to the other circuit breakers which are connected to the same bus as the breaker which failed to operate. By using a busbar image it is possible to automatically switch the trip command to the

different breakers depending on the switching conditions of the bus section at the time of breaker failure. This breaker back-up protection is also designed in the same modular system, and is housed in standard 19" chassis so that it can be combined with the bus protection.

4. CONCLUSIONS

To facilitate the design of complete protection schemes based on the available modules, selection tables are provided. Table 1 indicates a typical example of such a list for line protection.

Electronic protection packages which combine all the protective functions of a particular design in one cubicle respectively in one unit, facilitate the design, manufacture, installation and commissioning work. They also save space and contribute considerably to cost effectiveness by reducing the requirements imposed on the peripheral equipment such as the instrument transformers. They also help to increase considerably the reliability and the security of the entire relaying system, thus contributing towards an increased availability index of the power supply.

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