Power Systems Practicum

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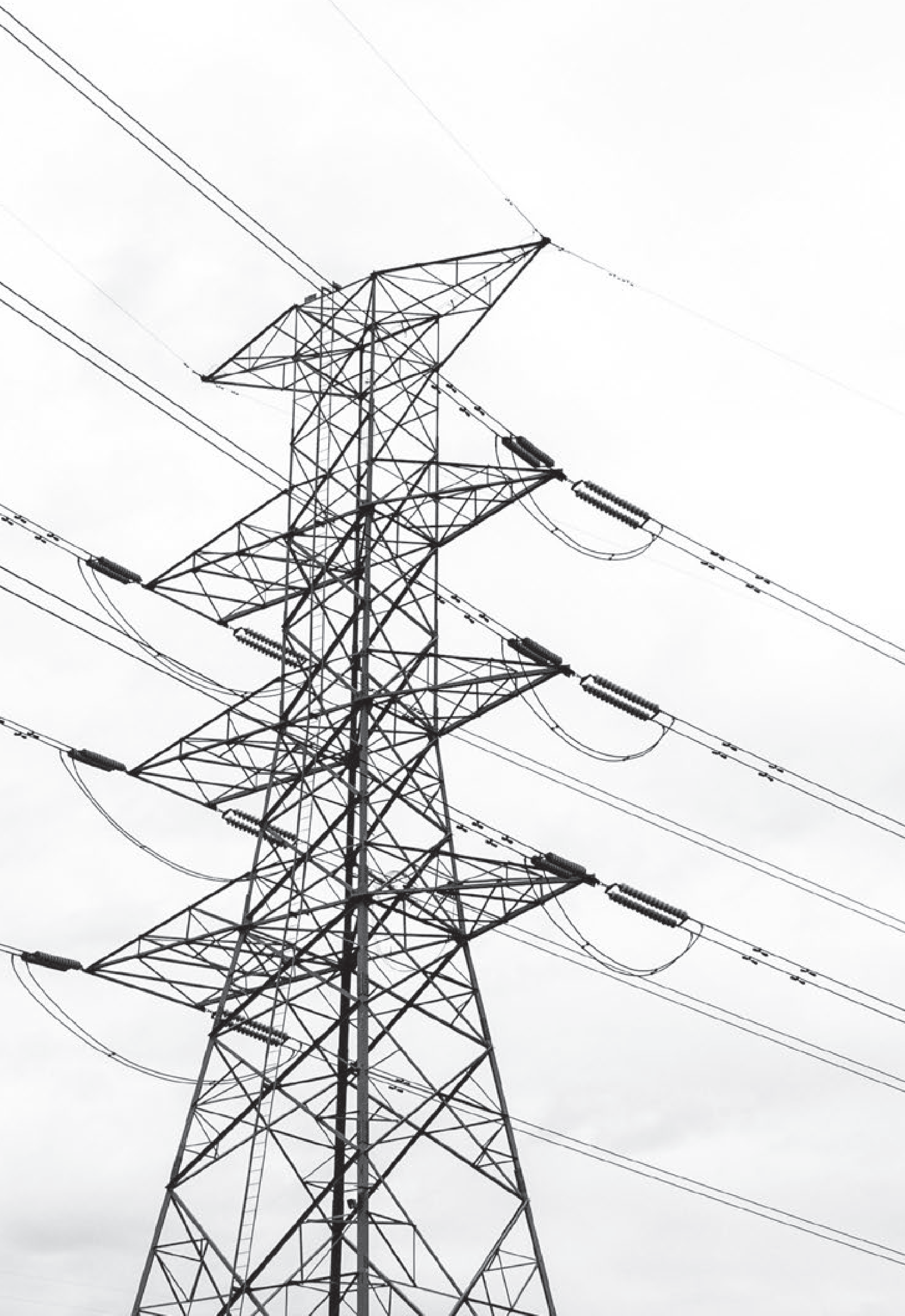

Chapter 1 Faults and Protection

Understanding the nature and characteristics of faults is essential in designing power system protection to ensure the safe and secure operation of a power system.

Chapter 1 Faults and Protection

1.1 Faults

Fault Characteristics

Electrical faults are deviations of voltage and current from their normal operating states. These can be classified as open-circuit fault, high impedance fault, short circuit fault, or a combination of them in complex situations. In general, most faults that occur in electrical systems are short circuit faults. For short circuit faults, the waveforms normally exhibit a drop in voltage and a rise in current. The lower the impedance of the short circuit path, the higher the fault current.

For open-circuit faults and high impedance faults there is no current or a very small current flowing along the circuits in question. These faults are dangerous as the fault current is absent or not sufficient to trigger current operated protection or to blow out fuses leaving the faulty circuit remain energised, without proper insulation and adequate safety clearance, which is hazardous to public safety. Therefore means to detect open-circuit faults are required.

Short Circuit Faults

The most common causes of electrical faults are equipment insulation failures, environmental factors, and human errors.

1. Power systems consist of various components: generators, transformers, cables, overhead lines, bushing, and switchgears. The insulation of such components will degrade over time due to aging. Growth of partial discharges is frequently the consequence of insulation aging, which will further degrade the insulation eventually ending up in insulation breakdown.

2. Environmental factors include many possibilities, for example, ice build-up and strong gusts may mechanically overload overhead line structures; heat waves may cause widespread fires and thus sagging of overhead line conductors due to temperature rise; over-grown vegetation may infringe electrical clearance forming short circuit path, water ingress to substation rooms such as caused by storm surge may lead to flashover in electrical equipment not designed for waterproof; pollution may cause dirt deposits on outdoor electrical equipment resulting in wear and breakdown of insulation; lightning strikes generate voltage surges and propagate the transient overvoltage waves to cause insulation breakdown and excessive current flowing through equipment.

3. Human errors are mainly due to violating safety procedures and unsafe acts, such as defeating interlock facilities to deplete the guard against the inadvertent energisation of an equipment before de-earthed; failure to keep sufficient safety clearance from live conductors such as heli-lifting too close to transmission overhead lines; damage of underground power cable during road excavation without performing cable presence detection beforehand.

When a fault occurs, if the associated power system protection does not operate fast enough to clear the fault, it may cause an explosion and fire, releasing high energy, high temperature and high pressure gases. If human beings are around, there is a likelihood

of serious injuries or fatalities. High energy arc flashes could even vaporise metal and insulation materials.

When there is an explosion sound from power equipment, it is likely caused by a power system fault. When an explosion is heard in the substation, people must evacuate from the substation as soon as possible and can return to site only when the situation is assessed to be safe by suitably trained personnel.

It is to be noted that the fault clearance device – the circuit breaker has a designed maximum fault breaking capacity. If such breaking capacity is exceeded, the fault current cannot be interrupted, and will result in permanent damage of equipment possibly coming along with explosion and fire.

In the event of a live high voltage circuit short circuited to earth, either as a result of human error or as an attempt to reclose a tripped circuit following a perceived transient fault, a vast fault current will flow. Even if the fault is cleared by protection within a timeframe of 100 milli-seconds, the associated voltage dip is very noticeable and would spread over a large area of that supply network. Voltage dip is a power supply quality issue worldwide. The disturbances that voltage dips cause to electrical equipment would affect production as well as people's daily lives in many ways.

Furthermore, if the associated power system protection does not clear the fault fast enough, upstream protection located at a higher voltage level will be activated. This will result in a shutdown of a larger portion of the power system, and may lead to system instability and blackouts in more serious scenarios.

Fault Current and Fault MVA

The amount of fault current that flows in the supply network depends on its source capacity. The highest fault level is when all available generators are put in service during the peak load periods. Fault current can be calculated from the impedance as seen from the fault point towards the supply source.

Since a very small fault current would be seen as a "big load" by the protection relay(s), it may not operate leaving the fault remain connected to the supply source. In a small power system, a minimum number of generators must be maintained online, sometimes more than required to meet the load demand, to ensure when a fault occurs there will be sufficient fault current for the protection system to detect. In old days, because many power systems were small, there were occasions when the load demand was so low that it could not even accommodate the minimum number of generators online for maintaining a sufficient fault level. As a result, lowering of protection settings was required. This occurred during the Chinese New Year period in Hong Kong in the early 1970s. Today, the problem of minimum fault current (insufficient fault level) is less of an issue as power systems are much larger and interconnected.

The maximum fault current allowed at a certain voltage level depends on the fault breaking capacity of the circuit breaker installed at that voltage level. In the early 1970s, the highest voltage level in Hong Kong was 132 kV as higher voltage level was not economically justifiable. The fault levels and the respective equivalent current values are as follows:

Nominal Voltage (kV)	Fault Level (MVA)	Fault Level (Equivalent A)
132	5,000	21,800
66	2,500	21,800
33	1,500	26,200
11	250	13,000

Currently, the fault breaking capacities at transmission and distribution levels have increased to:

Nominal Voltage (kV)	Fault Level (MVA)	Fault Level (Equivalent A)
400	44,000	63,500
275	30,000	63,000
132	7,200	31,500
22	700	18,300
11	380	20,000
LV 380 V	26	39,500

The increase in fault breaking capacity is contributed by circuit breaker technology advancements.

Understanding the fault current magnitude is important when carrying out testing and maintenance on power systems. Portable earth cables and earthing clamps (for equipment testing purpose) must be able to carry fault current up to 25 kA/40 kA. Although during testing, there may only be a small current going through the portable earth leads, there is a possibility of lightning stroke or an external fault inducing a large current in the earthed circuit. There may even be the possibility of erroneous switching to energise the earthed equipment from a remote end power source. Therefore, all earthing gears including earthing leads must be able to carry the prospective fault current.

There are 2 other design parameters for circuit breaker: the Fault Making Capacity and the Short Time Rating. The Fault Making Capacity is the maximum current that the circuit breaker can withstand upon closure of its contacts. It is the peak r.m.s. value of the current, measured in the first cycle of the current waveform after the closure of the circuit breaker. A multiplication factor of 2.55 is applied to the Fault Breaking Capacity to derive the Fault Making Capacity as there is a DC component in the current upon closing. (2.55 accounts for the peak value of the making current which consists of a DC component initially = 1.414 of the r.m.s. fault current value times the maximum asymmetry factor of 1.8 for the DC component.) The Short Time Rating is the fault current that the circuit breaker can allow to pass through for a duration between 1 sec and 3 sec. The above calculation is based on an AC system, for a DC system, the calculation would be different.

Open-circuit Faults

Open-circuit faults are less common than short circuit faults. Some examples are broken jumpers on distribution overhead lines, conductor detached from the underground cable joint due to mechanical stress etc. Open-circuit fault in a non-solidly earthed system would cause three-phase unbalance which could be detected by Neutral Displacement (ND) relay. Nowadays, digital relays with open conductor detection algorithm are available for the distribution network. Voltage sensors installed at distribution overhead line 11 kV pole mounted switches can serve to detect open-circuit faults. Advanced open conductor detection algorithm is also available in some Advanced Metering Infrastructure (AMI) which can provide either trip or alarm function as an enhanced feature.

Transformers in Parallel

In a power supply system, high voltage components are very often run in parallel to provide supply security and reliability. N-1 criterion is commonly adopted in power system design. This means that in case of the failure of any single component in the power network, the remaining components are still within operating limits without customer supply interruption. This criterion applies to the failure of the first component.

When stepping down from a higher voltage level to a lower voltage, for economy considerations ($/kVA and space requirements), larger capacity transformers are preferred to smaller capacity transformers because fewer transformers are required to be installed. However larger transformers due to lower impedances will give rise to greater fault currents. Since exceeding circuit breaker fault breaking capacity is not permitted, there is a limit on the number of transformers in parallel to avoid too low a fault impedance.

At transmission level substations, such as 132 kV substations where 400 kV is stepped down to 132 kV, because of the higher cost of transmission grade transformers, higher transformer impedance is specified to allow more transformers be connected in parallel to reduce the cost of maintaining N-1 reliability criterion.

At sub-transmission level substations where transmission voltage is stepped down to the distribution level, such as 132/11 kV, it is quite common as a design basis that only 2 transformers can be connected in parallel. With 3 transformers, the third one is run independently. An auto-switching scheme is put in place so that should any one of the three transformers trip out, the busbar section it supplies is switched to the other two transformers. On applying N-1 criterion to a substation of 3 transformers of identical rating, the “firm” supply capability of the substation is the sum of the rating of 2 transformers.

At lower voltage levels, it is not economical for equipment to be designed for high fault level to allow multiple transformers in parallel. Therefore, at distribution substations where utilities’ distribution supply voltage is stepped down to low voltage for customer supplies (380 V in the case of Hong Kong), an interlocking scheme is required on customers’ low voltage switchboard to prevent supply-side transformers be connected in parallel if more than one transformer is required to supply the loads. Failure of the interlocking scheme may result in fault level exceeding the switchgear fault breaking capacity which is an extremely hazardous situation.

1.2 Short-Circuit Limiting Couplings

Power systems are growing together with economic development: load growth, network growth and fault level growth. In Hong Kong, the major milestones of power system expansion were the years when the system voltage was upgraded.

In Hong Kong, the first 20 MW generator was commissioned in 1940. The first 11 kV network was built in 1950 or earlier. Subsequently, the highest system voltage was upgraded to 33 kV, 66 kV, 132 kV, 275 kV and 400 kV in 1953, 1961, 1966, 1981 and 1982 respectively. Today, 66 kV no longer exists. 33 kV is only adopted by very few customers such as in large water pumping stations and some railway networks.

When the power system expanded, the fault level also increased to a state beyond the withstandability of some network components. It might not be practical to upgrade all these components due to various resource and technical issues. These issues included outage arrangement, cost, time, and space. A pragmatic method is to split the network into 2 (or more) systems to reduce the source capacity in each system. However, this would lead to lower system security. The following innovative approach was suggested.

Short-circuit Limiting Couplings

A “Short-circuit Limiting Couplings” device was innovated (or invented) in 1960. As shown in Figure 1-1, the operating principle is that during normal load conditions, current and hence power can pass freely from system A to system B or vice versa. When a fault occurs, the nonlinear network will operate to short-circuit the series capacitor, leaving the series reactor to perform its current limiting function.

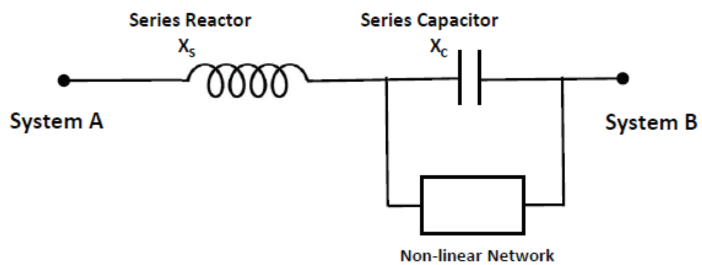

Figure 1-1 Concept of short-circuit limiting couplings

Figure 1-2 illustrates the implementation of this concept with the use of a circuit breaker to bypass the series capacitor.

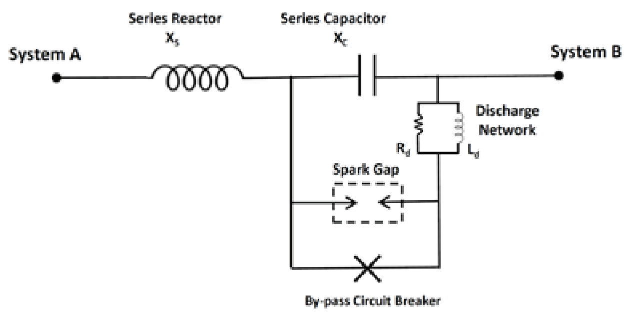

Figure 1-2 Short-circuit limiting couplings using by-pass circuit breaker

To be automatic and without the physical use of the by-pass circuit breaker, a saturable reactor is used in Figure 1-3. When a fault current is passing through the 2 systems, because the magnetic core of the reactor is saturated, it functions as a bypass during the fault current passage and reverts to its original state after the fault is cleared.

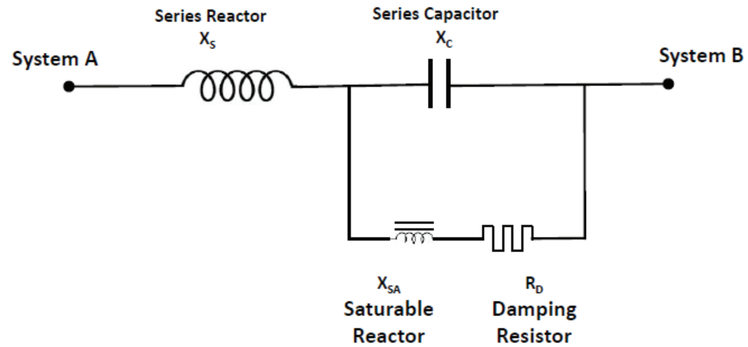

Figure 1-3 Short-circuit limiting couplings with saturable reactor

Two Short-circuit Limiting Couplings (SLC) devices were installed in Hong Kong around 1974. One SLC linked 2 power stations with generating capacity of 720 MW and 800 MW respectively. The other SLC linked 2 substations that were directly connected to the two power stations respectively. The transfer capacity of each SLC was 150 MVA.

After the installation, all the required pre-commissioning tests were carried out satisfactorily. On the day of commissioning, when the two SLCs were switched on to connect the two systems, system oscillation occurred. Continuous flickering of lights was seen for 2 minutes until the SLCs were switched off. The cyclic alternating pattern of lights brightening and dimming followed the power oscillation frequency.

Detailed examinations reviewed that all generator rotors showed some signs of damage due to the induction of various harmonics and sub-harmonics in the rotor circuit by the ferro-resonance of the reactor and capacitor combination of the SLCs. The SLCs were subsequently dismantled.

In the above case, the fault level problem arose as the system size grew. Introducing nonlinear elements as an engineering solution was innovative at the time for fault level control. However, the impact of the nonlinear devices on generating plants should be thoroughly assessed before implementation. The fault level problem at 132 kV level was resolved after the establishment of the 400 kV system. By then, the 132 kV network stepped down from the 400 kV system is segregated into several bulk supply zones for fault level control each supplied by a designated 400/132 kV substation. Between the 132 kV zones are interconnectors kept normally open at one end. The interconnectors will only be called upon under abnormal circumstances, such as for the transfer of loads when one zone has encountered the depletion of major equipment.

1.3 Protection Adoptions

In the early 1970s, the main transmission network's voltage level was 132 kV. During this time,132 kV equipment was only equipped with one single suite of protection. The investment in protection was minimal as protection was considered just a form of insurance and its failure should not cause catastrophic consequences. However, an incident did occur demonstrating that risk awareness was inadequate.

In the old days, it was a common practice to take some protection equipment out of service for pre-commissioning a new plant or circuit. For example, the high impedance busbar protection was taken out-of-service for the purpose of conducting primary injection for comparing the secondary currents of the Current Transformers (CTs) of the new circuit with existing circuits. At that time, the circuit breaker was of oil-filled type. The CTs were installed at the open bushings and could be accessed inside the circuit breaker bay.

In mid-August 1971, an intense typhoon named Rose attacked Hong Kong. During its passage, typhoon signal No.10 was hoisted. Under the strong gust, a piece of metal sheet was blown into an outdoor 132 kV substation in Kwun Tong area causing a busbar flashover. The flashover was likely to be both phase-to-phase and phase-to-ground. Unfortunately, the busbar protection was taken out of service because of the pre-commissioning test on the day before the typhoon. This resulted in an uncleared fault, as the single suite of feeder protection was a unit protection and could not detect an out-zone fault. The fault was eventually detected by the generator's Negative Phase Sequence Relays to trip out all the generators. Inevitably the event ended up in a system blackout. It took a few days for the power utility to restore electricity supply to all customers.

This incident drew the attention of top management. A protection expert from the United Kingdom was seconded to the company for a comprehensive review. Subsequently the review report recommended the company to adopt the "2 Main" protection systems for all 132 kV equipment. This redundancy approach was quite unique at that time, as many 132 kV networks across the world were also equipped only with single main protection.

The "2 Main" protections implementation concept proposed was to install 2 types of relays to provide 2 main protection schemes, each of a different operating principle to avoid common mode failure. For example, on a feeder protected by one set of current differential protection such as Solkor as the first main protection, the second main protection should be of a different protection operating principle. The emphasis is placed on fail-safe of the protection system in fault detection while accepting the slightly higher probability of relay maloperation as the number of protection equipment increases.

Distance protection was recommended as the second main protection as it could provide zone 2 and zone 3 protection to extend the protection reach beyond the circuit it protected to the remote end substation as a backup protection. The operating principle of distance protection is to calculate the impedance from voltage and current information during the fault condition to determine whether the fault is within its protected zone. At that time, transistorised electronic type distance relay was chosen in Hong Kong. (There were bulky electromechanical types of distance relay occupying one complete panel adopted in other countries at the time for protecting transmission line.) The electronic type TS and THS Distance relays adopted in Hong Kong were later found to be maloperation prone caused by defect of a specific transistor - the silver migration. The problematic electronic boards in the distance relays were subsequently replaced.

In the mid-1970s, economic growth in Hong Kong was fast, and so was electricity demand growth. The supply situation was tight at times when generation plant broke down. Underfrequency load shedding was put in place to disconnect pre-selected loads as a measure to arrest frequency drop caused by generation-load imbalance upon tripping of generator(s). The frequency drop if not arrested would put the remaining online generators into an inoperable regime (damage of steam turbine blades) causing more generators to trip out and further frequency dive. By automatically shedding loads in the earlier phase of the frequency decay, generation-load balance can be restored promptly to return the power system to a stable state. The underfrequency relay was also electronic in nature and there were few cases of maloperation due to internal transistor failures causing disconnection of some loads.

There was a practice of performing primary injection test when commissioning a new transmission circuit to confirm the correctness of CT polarity connection. This was to ensure the correct operation of Busbar Zone (BBZ) protection. The primary injection test required shutdown of busbar by section to facilitate a current loop on the primary side of the CTs for the test current to flow. This test, though needing a lot of preparatory work in arranging outages and safety provisions, was necessary for opening type oil circuit breaker switchgear because CTs were installed in situ and could be wrongly placed. (The integrity of busbar isolator auxiliary contacts is confirmed by wirings check.)

Starting in the 1980s, more and more SF_6 132 kV Gas Insulated Substations (GIS) were built. The practice of primary injection test continued initially despite the CTs were pre-installed at the GIS manufacturer's factory before delivery. Later, primary injection test at site was considered redundant for GIS while just retaining the flick test to confirm the correctness of CT polarity (carried out at pre-commissioning stage).

In 1988 a fire occurred in the cable gallery of the first 132 kV SF_6 GIS substation in Hong Kong. The entire substation was switched out by the operation of protection relays at the remote end substations. It was later discovered that both 2 main feeder protection at the local end did not operate because a portion of the 110 V DC multicore cables (for trip circuits) connected between the battery room and switchgears were damaged by the fire. It was interesting to note that in the substation the protection relays were installed in panels adjacent to the switchgear local control panel, yet the multicore cables were routed through the cable gallery which was a much longer path. It took one week to re-lay all the multicore cables. One of the main lessons to learn from this event was that apart from 2 main protection systems, the associated DC supply cables and multicore cables to the trip circuitries of the switchgear should be routed separately as far as practicable to reduce the risk of simultaneous failures.

The evolution of protection relays over the past half century can be summarised as transitioning from electromechanical types, to transistorised electronic types and finally to microprocessors. Before 1970, electromechanical relays dominated, followed by the popularity of electronic relays. By 1980, microprocessor-based relays started to emerge. Nowadays, microprocessor based relays are available for all types of protection relays, and cheaper than some electromechanical relays of similar protection principles still buyable in the market, e.g. OC/EF relays.

In 1980 the first interconnector to Mainland China for supplying electricity to Guangdong province was a 50 MVA OHL feeder-transformer from a 66 kV substation in Fanling to a 110 kV substation in Shenzhen. In 1981, a cross-harbour interconnection was established between the two power utilities in Hong Kong, for which besides conventional feeder protection, a unified underfrequency load shedding scheme was mutually agreed to align the frequency settings for several stages of load shedding prior to the decoupling of the interconnection. The distance protection for both interconnections included power swing blocking function. For the Hong Kong - Mainland China interconnection, the over-current protection included reverse-flow detection to ensure power flow was uni-directional from Hong Kong as Mainland China in the 1980s faced acute electricity supply shortages.

Experience has shown that protection relays can maloperate as well as fail to operate. When introducing new relays into the system, it is essential to assess the reliability comprehensively and perform trial in the live system, if possible, with tripping output defeated. It is until the reliability is proven that a new type of protection relay is accepted as a standard. There were a few maloperation cases during the initial introduction of electronic relays in the early 1970s as well as digital relays in the early 2000s.

1.4 Protection System

The role of a protection relay installed in a power system is to detect faults or abnormalities and to initiate tripping action so that the faulty component(s) can be quickly isolated by the minimum number of circuit breakers. The following is a typical illustration of the main elements of a protection system.

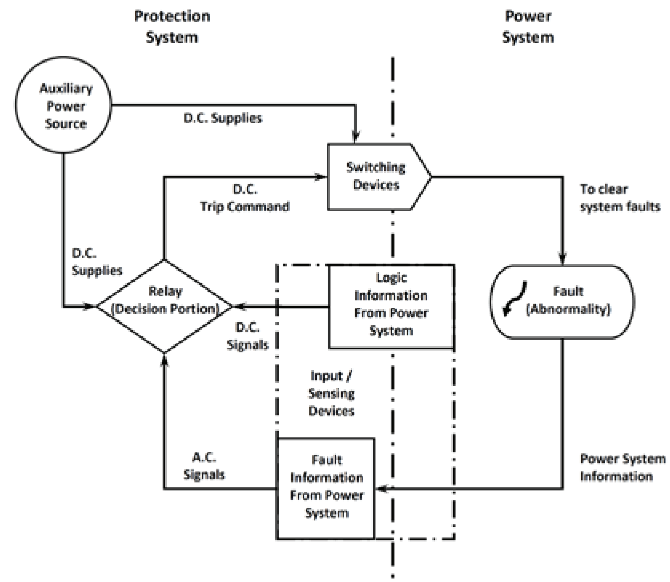

Figure 1-4 Protection system model

The protection system model shown in Figure 1-4 is typical in the early 1980s and illustrative of the basic function of a protection system at a single end. The major components of the protection system are relay input / sensing devices, relay decision portions, auxiliary power sources, and switching devices. Upon a power system fault, the fault information is detected by the CT and VT in AC form and sent to the relays. Logic information about the power system, for example, the busbar connection configuration, is input into the relays in DC form. Relays required DC power supply for fault analysis to determine whether it is an internal or external fault. The switching device in the diagram refers to the circuit breaker responsible for isolating the equipment guarded by the protection system.

The model in the diagram does not show the connection with the protection system at the remote end of the circuit to be protected. For example, for Solkor protection, pilot wires which are laid alongside the primary cable circuit, are embedded in a 19-pairs multicore cable with the inner 7 pairs reserved for the protection. Depending on the protection requirements, pilot wires can also be used for intertripping or other distance protection signalling functions. Intertripping is normally provided for feeder-transformer circuits. As distance protection is usually adopting the under-reaching scheme, the remote end distance protection zone information is provided to the local end via a telecommunication network and a protection signalling equipment to complete the distance protection scheme. (For a short length feeder, over-reaching scheme is adopted.)