Busbar Protection

ES 586b: Theory and Application of Protective Relays

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1. Significance of Busbar Faults

Busbars are very critical elements in a power system, since they are the points of coupling of many circuits, transmission, generation, or loads. A single bus fault can cause damage equivalent to many simultaneous faults and such faults usually draw large currents. So a high-speed bus protection is often required to limit the damage on equipment and system stability or to maintain service to as much load as possible. The term “bus protection” refers to protection at the bus location, independent of equipment at remote locations [1].

Most of faults incurred on buses are one phase to ground, but faults may be caused from different sources and a significant number are inter-phase clear of earth. In fact, a large proportion of busbar faults result from human error rather than the failure of switchgear components. Nowadays, with the advent of fully phase-segregated metal-clad gear, only earth faults are possible, therefore we only worry about earth fault sensitivity. Otherwise, the ability to detect phase faults clear of earth is an advantage, although the phase fault sensitivity need not be very high.

Differential protection is the most sensitive and reliable method for protecting a station bus. The phasor summation of all the measured current entering and leaving the bus must be zero unless there is a fault within the protective zone. For a fault not in the protective zone, the instantaneous direction of at least one current is opposite to the others, and the sum of the currents in is identical to the sum out. A fault on the bus provides a path for current flow that is not included in these summations. This is called the differential current. Detection of a difference exceeding the predictable errors in the comparison is one important basis for bus relaying. In dealing with high-voltage power systems, the relay is dependent on the current transformers in the individual circuits to provide information to it regarding the high-voltage currents. The following figures show typical examples of the location of current transformers that are used for this purpose. The arrowheads indicate the reference direction of the currents.

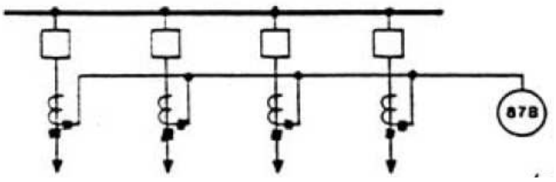

Figure 1-1: Single Bus Arrangement

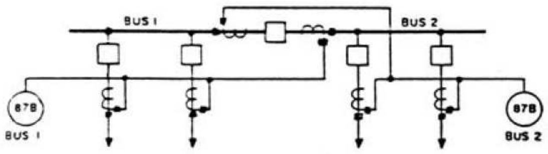

Figure 1-2: Multiple Bus Sections with Bus Tie Arrangement

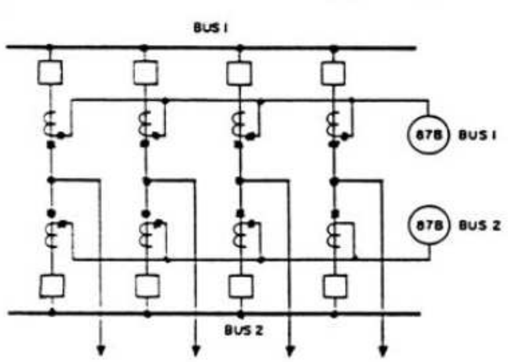

Figure 1-3: Double Bus Double Breaker Arrangement

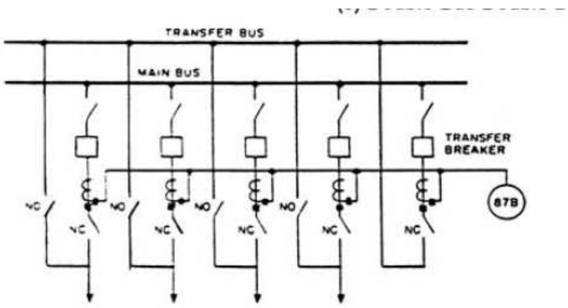

Figure 1-4: Main and Transfer Bus Arrangement

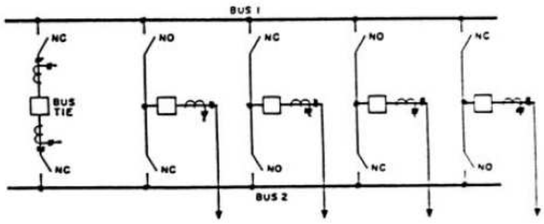

Figure 1-5: Double Bus Single Breaker with Bus Tie Arrangement

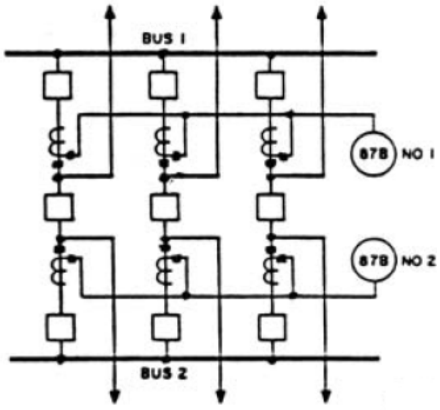

Figure 1-6: Breaker-and-a-half Arrangement

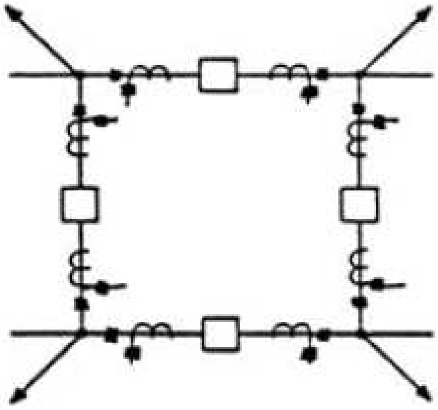

Figure 1-7: Ring Bus Arrangement

2. Busbar Protection Challenges

One of the challenges faced in protection of busbars is the CT saturation. Faults in busbars are different in the way that during an external fault, all of the other circuits connected to the bus contribute to that fault. Therefore the current through the breaker of the faulty circuit will be significantly higher than that for any of the other circuits. When this large current flows through CT, there is a very high likelihood that some degree of saturation will occur. A saturated CT will not deliver its appropriate current to the relay. As the current in other circuits are considerably lower, the degree of saturation is expected to be considerably lower. This may cause the relay to misinterpret the external fault for an internal fault. The relay must not misunderstand this current.

A common equivalent circuit for a CT (Figure 2-1) consists of a perfect transformer converting high current to low current (e.g., 600:5). The R_S is the internal secondary resistance of the CT, and the X is the excitation branch. When the CT is subjected to excessive flux, the CT becomes saturated, making much of the current to go into its excitation branch. This makes a large error in CT current sensing ability.

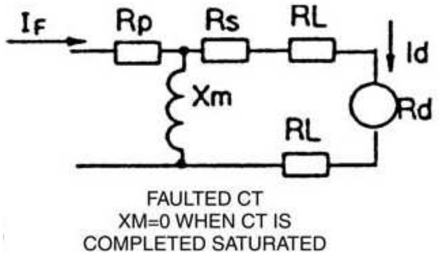

Figure 2-1: The Improved Over-Current Differential Bus Protection

DC can saturate the CT a lot more that AC, as a small amount of DC can saturate the CT and give rise to error. The L/R ratio of the power-system impedance, which determines the decay of the DC component of fault current, should strongly influence the selection of the bus protective relaying. Typically, the DC time constants for the different circuit elements can vary from 0.01 sec for lines to 0.3 sec or more for generating plants. The nearer a bus location is to a strong source of generation, the greater the L/R ratio and the slower the decay of the resulting DC component of fault current. Of the several available methods for solving the unequal performance of current transformers, four are in common use:

1. Eliminating the problem by eliminating iron in the current transformer (a linear coupler (LC) system)
2. Using a multi-restraint, variable-percentage differential relay which is specifically designed to be insensitive to DC saturation (CA-16 relay system)
3. Using a high impedance differential relay with a series resonant circuit to limit sensitivity to CT saturation (KAB relay system)
4. Using a Differential Comparator relay with moderately high impedance to limit sensitivity to CT saturation (RED-521)

3. Protection Requirements

Basic protection of a busbar is not much different from other components, but the key role of a busbar makes two of the requirements the more important: speed, and stability [2].

3.1. Speed

The primary objective of busbar protection is to limit the damage and also to remove busbar faults before back-up line protection, to maintain system stability. Formerly, a low impedance differential system was used which had a relatively long operation time, of up to 0.5 seconds. However, most modern protection schemes are a differential system capable of operating in a time of the order of one cycle. Of course, the operating time of the tripping relays should be added to this, but an overall tripping time of less than two cycles is achievable. Nowadays, with the introduction of high-speed circuit breakers, complete fault clearance may be obtained in approximately 0.1 seconds.

3.2. Stability

The stability of bus protection is very important. It should be noted that rate of fault in busbar are quite low (about one fault per busbar in twenty years). Therefore, a weakness in the stability of a protection system may have detrimental effects on the stability of the protection system. Formerly, this has led to some uncertainty in placing protection systems in busbars, or placing very sophisticated protection mechanisms. With better analysis of the system, these systems can be applied with correct settings. To achieve a higher stability index, most of the time two independent measurements are required for tripping command.

4. Busbar Protection Schemes

Quite a number of protection systems have been designed for busbars:

1. System protection used to cover busbars
2. Frame-earth protection
3. Differential protection
4. Phase comparison protection
5. Directional blocking protection

Of these, (1) is suitable for small substations only, while (4) and (5) have become obsolete. Detailed discussion of types (2) and (3) occupies most of our discussion.

4.1. System protection used to cover busbars

In systems where over-current or distance protection systems are present, busbars will be inherently protected. It should be noted that over-current protection will only be applied to relatively simple distribution systems, or as a back-up protection, which gives a considerable time delay, whereas distance protection provides cover for busbar faults in its second and possibly subsequent zones. In Any case, the protection acquired is slow and unsuitable.

4.2. Frame-Earth Protection

This method has been extensively used in the past. Various schemes are available for this type of protection each having a certain capability. The following subsections deal with each scheme. Many of them are still in existence and each can provide good service for a particular situation. However, the need to insulate the switchboard frame and provide cable gland insulation and the availability of alternative schemes using numerical relays, has contributed to a decline in use of frame leakage systems.

4.2.1. Frame-Earth Protection (Single-Busbar)

This protection scheme is basically an earth fault system which simply measures the fault current flowing from the switchgear frame to earth. A CT is mounted on the earthing conductor and is used to energize a simple instantaneous relay as shown in Figure 4-1. Meanwhile, no other earth connections of any type, including incidental connections to structural steelwork are allowed. This guarantees that:

1. The principal earth connection and current transformer are not shunted, thereby raising the effective setting. An increased effective setting gives rise to the possibility of relay mal-operation. This risk is small in practice.
2. Earth current flowing to a fault elsewhere on the system cannot flow into or out of the switchgear frame via two earth connections, as this might lead to a spurious operation.

Careful construction of the system is of utmost importance in this case, as the switchgear must be insulated from ground, usually by standing it on concrete and the foundation bolts must not touch the steel reinforcement.

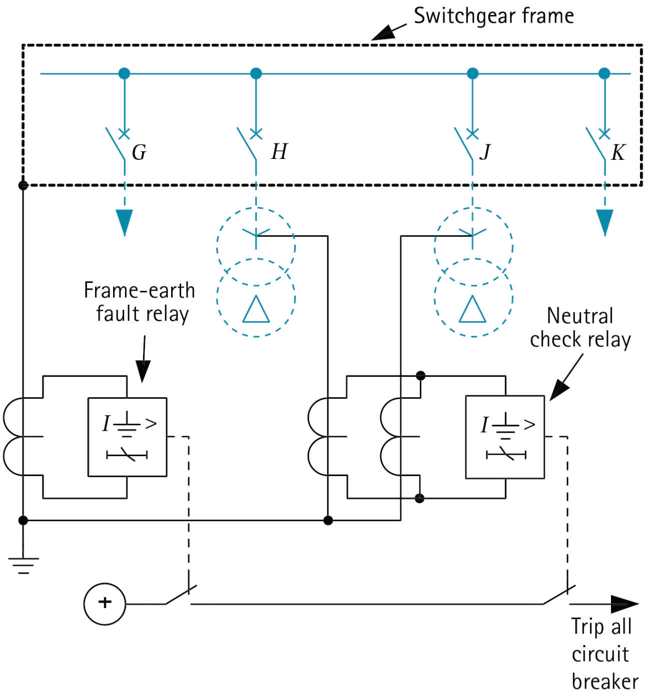

Figure 4-1: Single-zone Frame-earth Protection

It is important that the impedance between the frame and ground should not be very high, as the current carried would not be large enough to be sensed by relay. It also ensures that the potential of the frame does not exceed a certain limit.

4.2.2. Frame-Earth Protection (Sectioned Busbars)

An alternative scheme to that of 4.2.1 is to divide the busbar into sections and protect them separately. To achieve this type, the frame must be divided and all sections insulated from one another so that each can be earthed using a dedicated earth conductor. Obviously, each section will have a separate CT and relay. Ideally, the section switch should be treated as a separate zone, as shown in Figure 4-2, and provided with either a separate relay or two secondaries on the frame-leakage current transformer, with an arrangement to trip both adjacent zones. The individual zone relays trip their respective zone and the section switch.

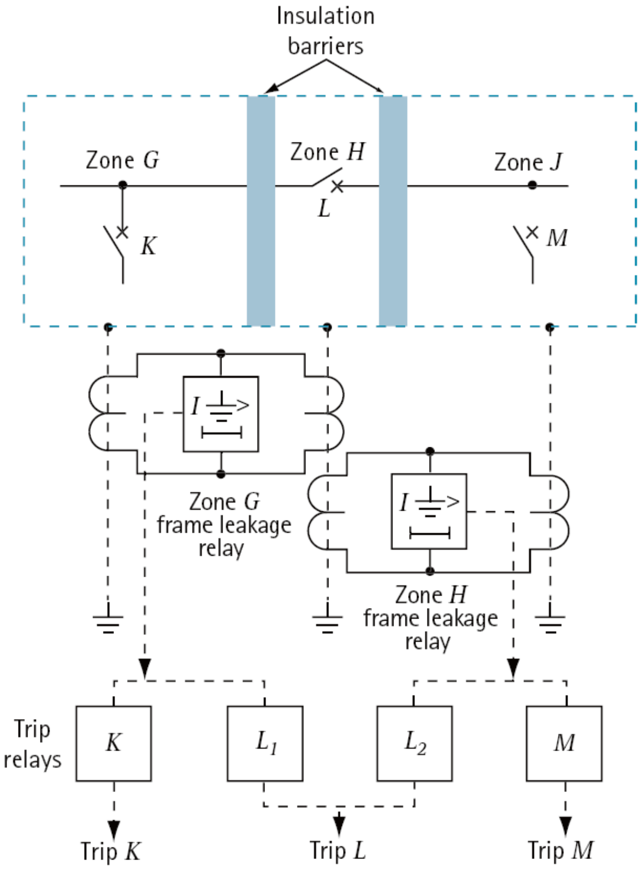

Figure 4-2: Three Zone Frame Earth Scheme

4.2.3. Frame-Earth Scheme (Double Bus Substation)

Generally it is not possible to have separate insulation between the metal enclosures of the main and auxiliary busbars. Therefore protection is generally provided similar to single bus installations, except that now circuits connected to the auxiliary bus are tripped for all faults.

4.2.4. Frame-Earth Protection (Check System)

A check system should be provided on all equipments (except the small ones), to protect against contingencies resulting from operation due to mechanical shock or human error. Faults in the low voltage auxiliary wiring must also be prevented from causing operation by passing current to earth through the switchgear frame. A useful check is provided by a relay energised by the system neutral current, or residual current. If the neutral check cannot be provided, the frame-earth relays should have a short time delay. When a check system is used, instantaneous relays can be used, with a setting of 30% of the minimum earth fault current and an operating time at five times setting of 15 milliseconds or less.

4.3. Differential Protection

The differential protection comes directly from Kirchhoff's current law. All of the currents are added together and the relay is only activated once the sum of the currents is not zero, i.e. a fault is occurred on the busbar. The different in currents represents the fault current. One way to implement this arrangement is to use one relay and put all CTs in parallel (Figure 4-3). This also gives earth fault protection which was thought to be sufficient. Moreover, if the CTs are connected as a group for each group of three phases (Figure 4-4), it is also possible to add phase fault protection to the system.

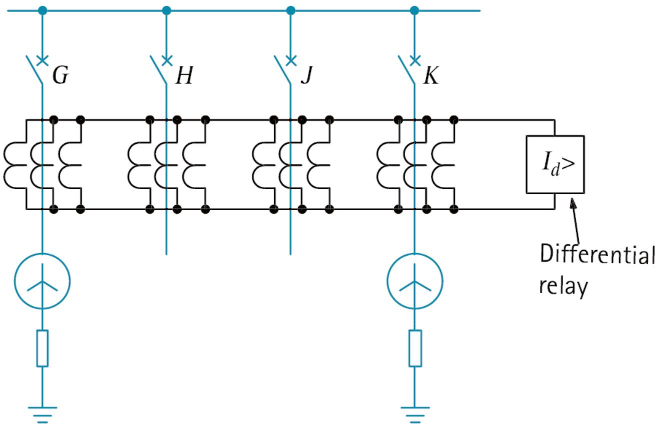

Figure 4-3: Basic Circulating Current Scheme

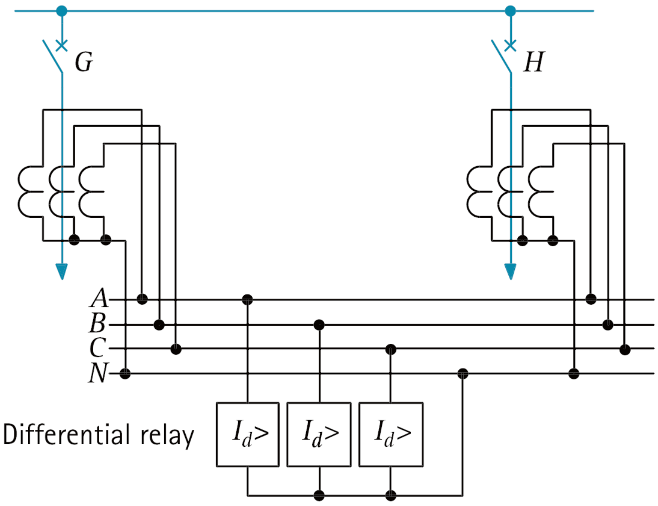

Figure 4-4: Three-Element Relay

4.3.1. Differential Protection for Sectionalized Busbars

For divided busbars, each section can be protected separately. However, the zones must overlap so that faults in the common areas are cleared by both zones (Figure 4-5).

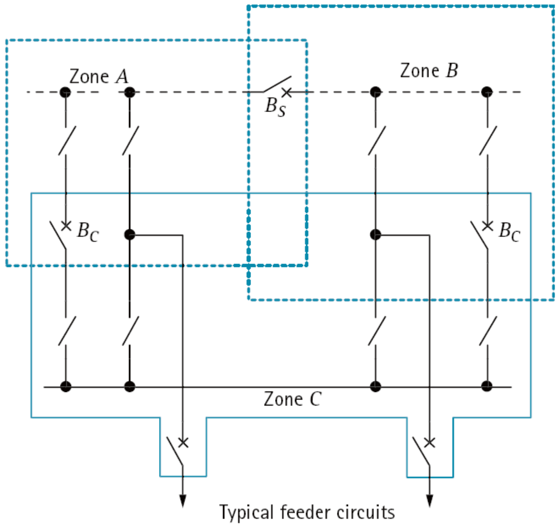

Figure 4-5: Zones of Protection for Sectionalized Busbars

Ideally, the zones of protection should overlap and their overlap occurs on a circuit breaker, so that it is shared between the two zones. So it is necessary to have CTs on both sides of the breaker, which is not possible with all types of breakers. When CTs are on both sides of the breaker, all faults can be cleared (Figure 4-6). If both CTs are located on one side of the breaker, the zones are still overlapping but a fault between the CT and breaker can not be completely isolated (Figure 4-7); this region is known as “short zone”. Such a fault will cause the breaker to operate, but if there is a source of power in the circuit, it can still feed the fault. A special protection can be provided to detect faults in the “short zone” to send a trip signal to the remote end of the circuit, where a generator might be present.

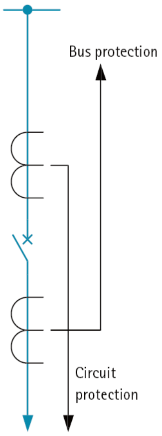

Figure 4-6: CTs on both Sides (No Unprotected Region)

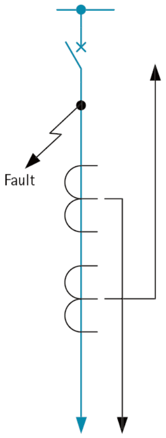

Figure 4-7: CTs on One Side Only (Fault Shown Not Cleared)

4.3.2. High-Impedance Differential Protection

High-impedance protection schemes also use conventional CTs, but they have solved the problem of unequal current transformer performance by loading them with a high impedance relay (Figure 4-8).

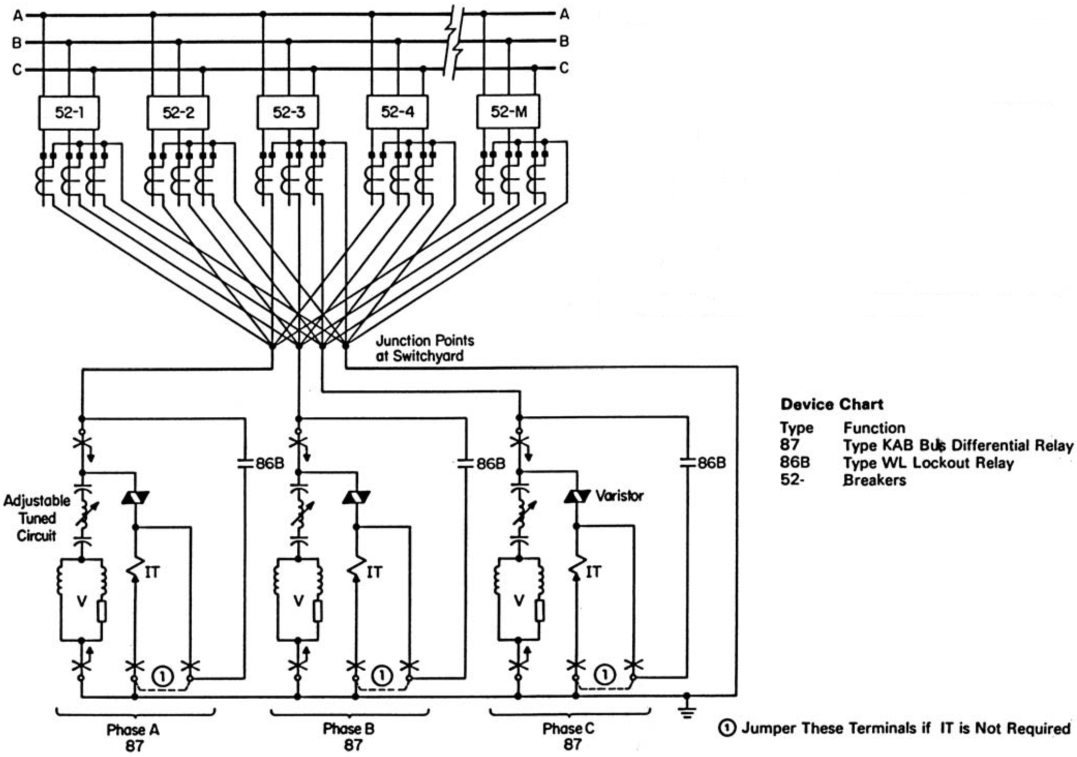

Figure 4-8: External Connection of Bus Differential Relay

Here the false differential currents are forced to go through CTs rather than relay operating coil. Actually, the high impedance differential concept comes from the above "improved over-current differential" approach. It uses a high impedance voltage element instead of "a low impedance over-current element plus an external resistor."

The high impedance differential KAB relay consists of an instantaneous overvoltage cylinder unit (V), a voltage-limiting suppressor (varistor), an adjustable tuned circuit, and an instantaneous current unit (IT). On external faults, the voltage across the relay terminals will be low, essentially 0, unless the current transformers are unequally saturated. On internal faults, the voltage across the relay terminals will be high and will operate the overvoltage unit. Since the impedance of the overvoltage unit is 2600O, this high voltage may approach the open-circuit voltage of the current transformer secondaries. The varistor limits this voltage to a safe level. Since offset fault current or residual magnetism exists in the current transformer core, there is an appreciable dc component in the secondary current. The dc voltage that appears across the relay will be filtered out by the tuned circuit, preventing relay pickup. The IT current unit provides faster operation on severe internal faults and also backup to the voltage unit. The range of adjustment is 3 to 48 A. The KAB relay has successfully performed operations up to external fault currents of 200 A secondary and down to an internal fault current of 0.27A secondary. Its typical operating speed is 25 msec.

4.3.3. Low-Impedance Differential Protection

The principle of this system is shown in outline in Figure 4-9. If the current transformers are ideal, the functioning of the system is straightforward. The transformers will, however, have errors arising from both Watt-metric and magnetising current losses that cause deviation from the ideal, and the interconnections between them may have unequal impedances. This can give rise to a ‘spill’ current through the relay even without a fault being present, thus limiting the sensitivity that can be obtained. Figure 4-10 illustrates the equivalent circuit of the circulating current scheme.

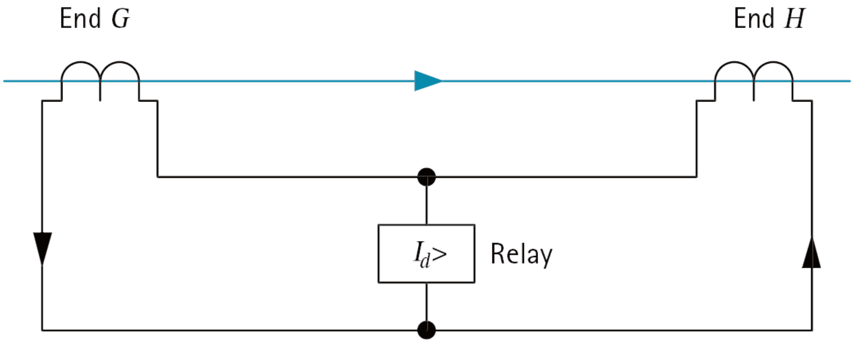

Figure 4-9: Differential Protection Scheme

If a high impedance relay is used, then unless the relay is located at point J in the circuit, a current will flow through the relay even with currents I_{Pg} and I_{Ph} being identical. If a low impedance relay is used, voltage FF' (Figure 4-11) will be very small, but the CT exciting currents will be unequal due to the unequal burdens and relay current IR will still be non-zero.

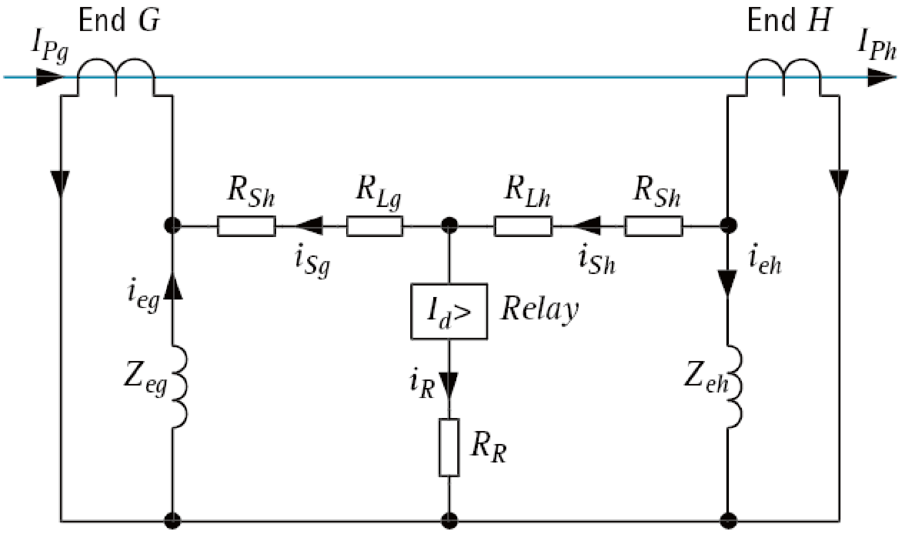

Figure 4-10: Low-Impedance Differential Protection

When the balancing current transformers of a unit protection system differ in excitation characteristics, or have unequal burdens, the transient flux build-ups will differ and an increased ‘spill’ current will result. There is a consequent risk of relay operation on a healthy circuit under transient conditions, which is clearly unacceptable. One solution is to include a stabilising resistance in series with the relay. Details of how to calculate the value of the stabilising resistor are usually included in the instruction manuals of all relays that require one. When a stabilising resistor is used, the relay current setting can be reduced to any practical value, the relay now being a voltage-measuring device. There is obviously a lower limit, below which the relay element does not have the sensitivity to pick up. Relay calibration can in fact be in terms of voltage. Figure 4-11 shows the different electromechanical forces (EMF) achieved with high-impedance and low-impedance relays. Lines GG' and HH' show EMF for high-impedance relay and lines GG" and HH" show EMF for low-impedance relay.

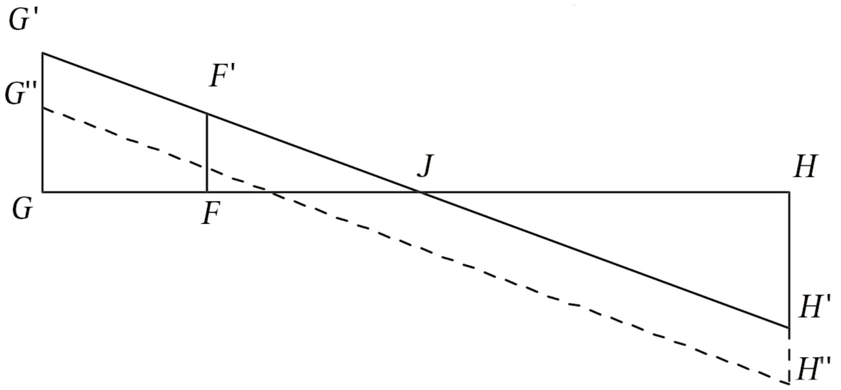

Figure 4-11: Electromechanical force with different relays

4.4. Digital Busbar Protection

Digital relay application has lagged behind that of other protection functions. Usually static technology is still employed in these schemes, but now digital technology has become mature enough to be considered. Multiple communications paths have provided relays with links to various units.

The philosophy adopted is one of distributed processing of the measured values, as shown in Figure 4-12. Feeders each have their own processing unit, which collects together information on the state of the feeder (currents, voltages, CB and isolator status, etc.) and communicates it over high-speed fibre-optic data links to a central unit. For large substations, more than one central unit may be used, while in the case of small installations, all of the units can be co-located, leading to the appearance of a traditional centralised architecture.

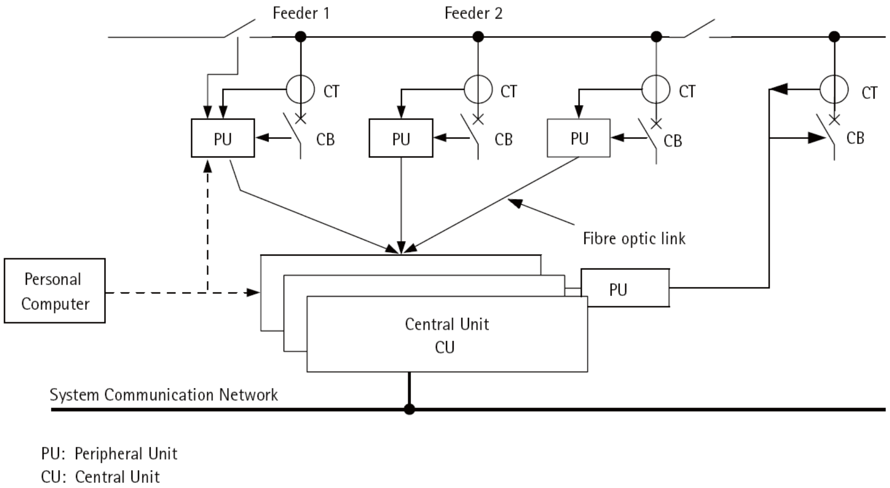

Figure 4-12: Architecture for digital relay protection

The central unit performs the calculations required for the protection functions. Available protection functions are:

1. protection
2. backup over-current protection
3. breaker failure
4. dead zone protection

In addition, monitoring functions such as CB and isolator monitoring, disturbance recording and transformer supervision are provided.

5. References

[1] Elmore, W.A., “Protective Relaying Theory and Applications”, Basel, New York, 2004
[2] ALSTOM, “Network protection and automation guide”, ALSTOM, 2002