BUS DIFFERENTIAL PROTECTION IN INDUSTRIAL SYSTEMS WITH GENERATORS CONNECTED DIRECTLY TO THE MAIN DISTRIBUTION BUS

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Abstract – In industrial facilities with on-site generation there are two major approaches to connect generators to the main distribution busbar. One is to connect generators through step up delta-wye transformers with low resistance grounded wye on the busbar side. The second common method is to connect generators directly to the main distribution busbar and use low resistance grounding or hybrid grounding in the generator neutral. A grounding resistor in the step up transformer's wye side neutral or in the generator neutral will limit the ground fault in the main distribution system. When busbar differential protection is used on the main busbar, sensitivity for bus ground faults has to be evaluated to ensure detection of limited low level ground faults. While step up transformer grounding resistors can be selected to allow ground faults of higher magnitudes detectable by bus differential protection, the choice of grounding resistor is more complex when generators are connected directly to the main busbar. In such systems, a grounding resistor in the generator neutral limits the generator fault to protect the alternator core from excessive damage. At the same time, busbar differential protection needs to detect a limited low magnitude ground fault on the bus. This paper discusses considerations to select the main distribution busbar differential protection type, CTs and relaying scheme to enable detection of busbar ground faults limited by the generator low resistance grounding resistor.

Index Terms — Bus differential protection, current transformer, saturation, magnetizing current, protection sensitivity, protection stability, generator grounding, sensitive ground fault protection.

I. INTRODUCTION

Bus differential protection is an important part of a protection system. In industrial plants bus differential protection is often used to protect the main power distribution buses. Bus differential protection provides the most effective protection for the most critical switchgear in the electrical system in the event of electrical faults.

With the objective to achieve speed, selectivity, sensitivity and reliability [1] of protective relaying schemes and systems, electrical engineers consider the technical requirements of electrical system components such as generators, transformers, motors, circuit breakers, busbars, etc. At the same time, the technical characteristics and economics of components of protective relaying schemes, such as current transformers (CT), voltage transformers (VT), relays and communication requirements are analyzed to achieve the most cost effective and technically correct and feasible solution.

The choice of a busbar protection scheme is based on the technical and commercial criteria. Selections vary from conventional busbar differential protection schemes such as high impedance or low impedance [1], partial busbar differential scheme [2], or communication based protection schemes such as reverse zone blocking [3].

This paper discusses conventional busbar differential protection schemes and ways to achieve protection speed, selectivity, sensitivity and reliability in typical industrial electrical networks and therefore satisfy the main protection system objectives.

Section II provides an overview of the two most common conventional bus differential schemes: high impedance and low impedance. It summarizes the importance of proper CT selection and the way CT parameters influence the performance of high impedance type differential protection. This section discusses the stability of differential protection for the maximum out-zone faults, and sensitivity for the minimum in-zone faults to achieve protection security and dependability.

Since the minimum expected in-zone fault often depends on the method of system grounding, Section III discusses the most common grounding methods in medium voltage networks. Neutral grounding with current limiting resistance is often used in medium voltage distribution networks and has a direct impact on the minimum expected fault and required sensitivity of the busbar differential protection.

Section IV presents a practical example of a busbar protection scheme used on a project and challenges in selection of protective relays and CTs to achieve stability and sensitivity of the differential protection. The same example is used in Section V to discuss one of the options to improve sensitivity, and modification of a conventional differential scheme to achieve the objective.

Finally, Section VI presents conclusions and recommends steps and measures that can be applied to insure adequate protection of power system buses with conventional busbar differential schemes.

II. BUS DIFFERENTIAL PROTECTION SCHEMES

A. Low Impedance Bus Differential Protection

Low impedance bus differential relays' current inputs represent low impedance to the flow of CT secondary current. Fig. 1 shows a typical one line diagram with two overlapping zones of low impedance bus differential relays.

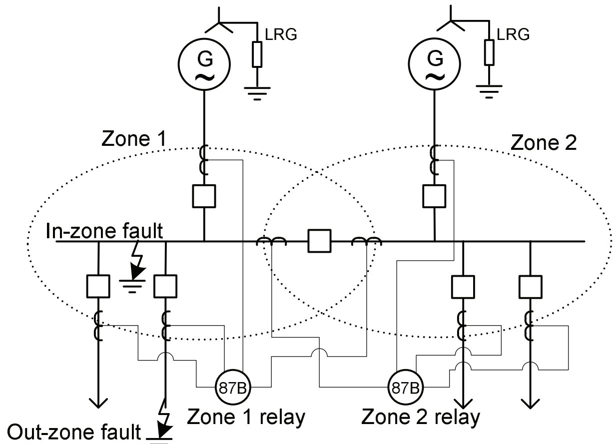

Fig. 1 Low Impedance Bus Differential Protection – CT Connections

The low impedance bus differential relays usually have a dedicated current input for each phase from each CT in the scheme. Due to the limited number of current inputs in one low impedance bus differential relay, bus differential zones with multiple feeders usually require multiple low impedance bus differential relays to protect one zone.

Dedicated current inputs to the relay from each CT in the scheme allows the use of different CT ratios and dissimilar CT characteristics in one bus differential zone. It also allows that the same CTs used for other relays and meters are connected to the low impedance bus differential relay CT input. The low impedance bus differential relay can compensate for the different CT ratios by using CT ratio correction on each input to normalize the currents to a common base. Since the low impedance differential relay uses individual CT current measurements from each feeder and each phase, the relay can be used for the feeder breaker failure protection and end-zone fault detection [4] when fault occurs on the line side of the breaker between the breaker and the bus differential protection CT.

Low impedance bus differential relays usually have a settable biased operating characteristic. Since the CTs used in the scheme may have uneven magnetizing characteristics, unbalanced currents may appear in normal operating conditions even with perfectly normalized CT secondary currents. During through faults i.e., out-zone faults, the level of unbalanced currents will rise as a function of the fault current level due to uneven saturation of the CTs included in the scheme. In order to avoid false operation due to unbalanced currents and maintain high sensitivity for in-zone faults when the unbalanced current may be small, the variable percentage bias restraint characteristic is applied. The biased characteristic will restrain the transient differential currents resulting from CT saturation during through faults to ensure stability. During heavy in-zone faults the biased characteristic may be suppressed to ensure operation of the differential relay. For low level in-zone faults, the relay will operate at the minimum pickup current of the biased operating curve.

Sensitivity of a low impedance bus differential protection depends predominantly on the ratio of the CTs used in the scheme, CT magnetizing characteristics, maximum normal load current of any feeder encompassed by the bus differential zone, and available minimum pickup current set-point available in the relay.

B. High Impedance Bus Differential Protection

High impedance bus differential relaying schemes use CT secondaries connected in parallel and wired to one common input of the high impedance bus differential relay. CT secondaries connected in parallel are from the same phase of all feeders in the bus differential zone. Therefore, high impedance differential schemes have three CT inputs, one for each phase, regardless of the number of feeders in a protection zone. Fig. 2 shows a typical one line diagram with two overlapping zones of high impedance bus differential relays.

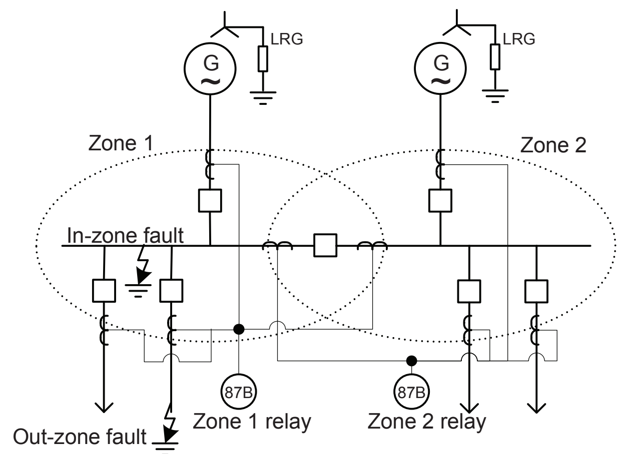

Fig. 2 High Impedance Bus Differential Protection – CT Connections

The CT secondaries are connected in parallel with the series connection of high impedance and relay operating coil. In case of out-zone faults, high impedance will force the unbalanced differential current to flow through the CTs instead of the relay operating coil and induce the voltage across the relay operating circuit lower than the relay operating voltage.

In case of an in-zone fault, the high impedance of the differential relay will force the secondary current through the exciting impedance of the CTs inducing the voltage higher than the relay operating voltage. Therefore, voltage across the differential relay high impedance and operating coil will be high enough to operate the relay. A varistor, or a similar device across the relay high impedance and operating coil, provides the secondary circuit protection by limiting the voltage to safe level [5]. Usually high impedance bus differential relays are set in Volts as opposed to low impedance bus differential relays whose operating characteristic is defined in Amps.

To ensure stability for out-zone faults the voltage setting of busbar protection should satisfy the following condition [5]:

$$V_{set} > \frac{I_{f\max}}{N} \times (R_{ct} + R_L) \tag{1}$$

where

V_{set}	setting voltage
I_{fmax}	maximum primary through-fault current
N	busbar differential protection CT ratio
R_{ct}	busbar differential protection CT internal resistance
R_L	longest lead loop-resistance between relay and CT

Primary sensitivity at voltage setting V_{set} is equal to [5]:

$$I_{op\min} = N \times (I_r + n \times I_m + I_{res}) \tag{2}$$

where

I_{opmin}	minimum primary fault current that can be detected by busbar differential protection
I_r	relay operating current at setting voltage V_{set}
I_m	busbar differential protection CT magnetizing current at setting voltage V_{set}
n	number of CTs connected in parallel in the busbar differential zone
I_{res}	leakage current of the varistor

The main parameters used in Equations (1) and (2) are shown in Fig. 3 as a single phase representation of a high impedance bus differential protection circuit with n = 3 feeders. Equivalent CT circuits are represented with ideal transformation, internal resistance R_{ct} and excitation voltage V_{exc} across the exciting impedance X_m. External CT leads have a resistance of R_L and for simplicity they are assumed to be equal for all CTs. With an in-zone bus fault current I_{op} that causes the bus differential relay 87B to trip, operating voltage V_{op} will reach or exceed the setting voltage V_{set}, and cause the relay operating current I_r to flow through the high resistance R_R and relay operating coil. The primary fault current contributions in individual feeders I_{F1}, I_{F2} and I_{F3} are reflected on the CT secondary sides as I_{f1}, I_{f2} and I_{f3}.

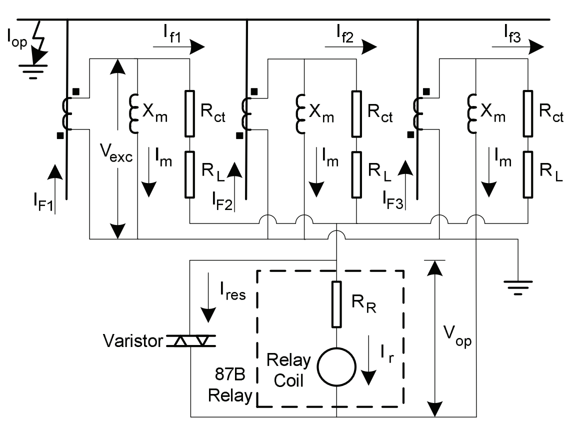

Fig. 3 High Impedance Bus Differential Protection Circuit

To ensure that the operating point of a high impedance differential relay is on the linear part of the CT magnetizing characteristic, the knee point voltage V_{kn} requirement for the differential protection CT should be [5]:

$$V_{kn} = k \times V_{set} \tag{3}$$

where

V_{kn}	knee point voltage
V_{set}	setting voltage
k	CT saturation factor, the value of k is recommended by relay manufacturer

Typical CT magnetizing characteristic is shown in Fig. 4.

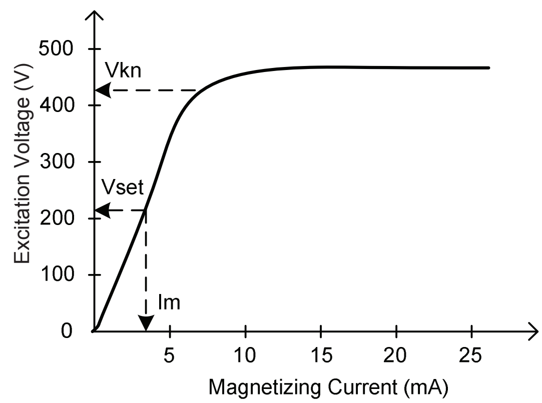

Fig. 4 Current Transformer Magnetizing Characteristic

Equations (1), (2) and (3) show that CT selection has a significant influence on the performance of the high impedance bus differential protection. From Equation (1) and (3) it can be concluded that CTs used in the scheme impact stability for out-zone faults. Secure operation requires high knee point voltage V_{kn}. Equation (2) shows that CTs used in the scheme impact sensitivity for in-zone faults. Dependable and sensitive operation of high impedance differential protection for in-zone faults is achieved with lower magnetizing current I_m and lower CT ratio N. Bus differential zones with smaller number of feeders i.e., a smaller number n of CTs connected in parallel, have better sensitivity.

III. TYPICAL GROUNDING METHODS IN MEDIUM VOLTAGE NETWORKS

The required sensitivity of busbar differential protection is determined by the minimum fault expected in the network. Medium voltage distribution networks are often low resistance grounded. In low resistance grounded systems, resistance is selected to limit line to ground fault current between 100 A and 1000 A, with 400 A being typical [6]. Ground fault current limited by the neutral grounding resistors is usually considered the minimum fault current in the system.

A. Network Low Resistance Grounding – Generators Connected via Step-up Transformers

In industrial facilities with on-site generation one approach to connect generators to a medium voltage power distribution bus is via step-up transformers as shown in Fig. 5. Step-up transformers are connected in a delta-wye configuration with the low resistance grounded wye on the network busbar side. A typical example would be a 34.5 kV power distribution system powered by 13.8 kV generators connected via step-up transformers.

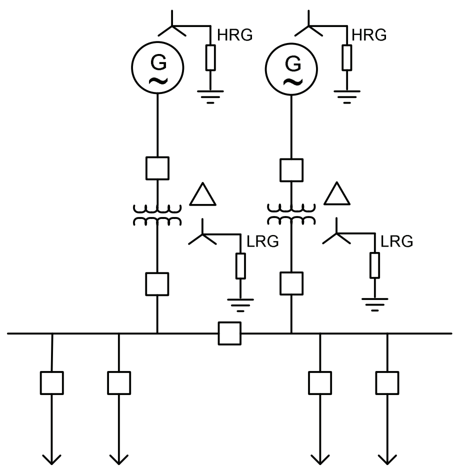

Fig. 5 Generators Connection – Step-up Transformers

When step-up transformers are used, generators are often equipped with a high resistance or high impedance grounded neutral that limits the generator ground fault current to a value of 5 A to 7 A [7]. The high resistance limiting current is selected to be higher than the capacitive current of the system. Due to the step-up transformer delta connection on the generator side, there is no contribution to generator phase to ground faults from the power distribution network. With generator phase to ground faults limited by high resistance or high impedance, ground fault damage to the alternator can be minimized. An example of an alternator damage curve is shown in Fig. 6. The curves come from the generator manufacturer for faults that occur inside the generator. With fault contribution from all generators it is expected that phase to ground fault alternator damage will be negligible.

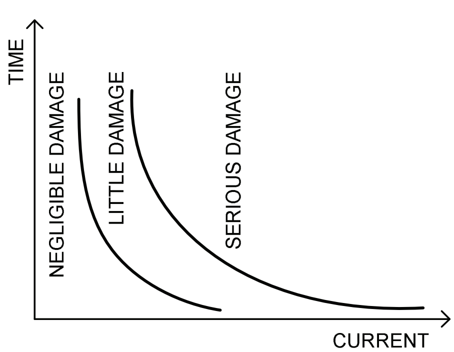

Fig. 6 Example of an Alternator Damage Curve

On the power system distribution side, step-up transformer neutrals are grounded by low resistance. The value of low resistance grounding in the transformer neutral can be selected so that the ground faults are detectable by busbar differential relays that protect the power distribution network buses.

While connecting generators to the power distribution network via step-up transformers is advantageous in terms of dependability of the network busbar differential protection, this approach is expensive and not always commercially justified. Better conditions to detect phase to ground faults on the busbar is usually not a sufficient reason to justify the use of generator step-up transformers. Typically, the decision to install step-up transformers is made when the power distribution system voltage level needs to be higher than the generation voltage level for other technical reasons such as: total maximum load, main distribution bus ampacity, short circuit level or possible voltage drop issues on long main distribution feeders.

B. Low Resistance Grounding – Generators Connected Directly to the Main Distribution Bus

Another way to connect generators to power distribution systems in industrial facilities is direct connection to the main distribution bus. High ampacity ratings and short circuit ratings of modern switchgear equipment are meeting a wide range of power, ampacity and short circuit requirements in industrial plant electrical systems and allow design and implementation of the main power distribution on the generator voltage level.

For example, it is common to use 13.8 kV main power distribution buses to distribute 40 – 50 MW of electrical power and have both generators and power distribution on 13.8 kV level. With the use of short circuit limiters and by connecting on-site generators on selected points on the main power distribution buses, it is possible to increase power distribution capabilities even further and still use the same voltage level.

Direct connection of generators to the distribution network is cost effective, but the influence of generator grounding on the protection of the distribution network has to be considered in the design. Various methods of generator grounding are presented in [8] and generator protection methods are discussed in [9]. One common approach in medium voltage industrial networks is to use low resistance grounding as shown in Fig. 7.

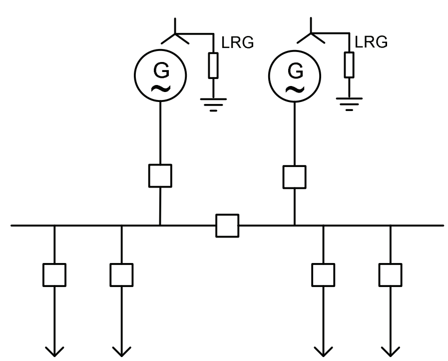

Fig. 7 Generators Direct Connection – Low Resistance Grounding

The number of generators and the number of outgoing feeders depends on the total maximum load, type and size of generators, sparing requirements and power distribution network topology. It is typical to have a high number of feeders in one busbar differential zone. Minimum bus differential in-zone faults are fully dependent on the selection of low resistance in the generator neutrals.

The requirements for minimum alternator damage and bus differential protection sensitivity may be mutually exclusive and may need to be balanced.

The number of generators connected to the network may be different for different plant operating conditions. With a higher number of generators running in parallel, due to the higher ground fault contribution, a faulted generator's alternator may sustain serious damage. To minimize phase to ground fault damage to the alternator iron core, the neutral resistor should limit the current to a low value.

For dependable operation of busbar differential protection, it is desirable to have higher fault magnitudes. The operating condition with minimum generators running or one generator running will produce the lowest magnitude of phase to ground fault and will be the most critical to determine if busbar differential protection will detect the fault.

As discussed in Section II, CT parameters impact sensitivity of bus differential protection. Bus differential protection schemes that use lower CT ratio N and bus differential zones with a smaller number of feeders i.e., smaller number n of CTs connected in parallel, have better sensitivity. In low resistance grounded networks with generators directly connected to the bus, generators and main distribution buses are on the same voltage level so high currents are expected in the distribution system and therefore high CT ratio N is normally used. The number n of CTs connected in a bus differential zone can also be quite high in large industrial plants. So both parameters CT ratio N and number n of CTs in one differential zone are usually unfavorable for sensitive operation of busbar differential protection.

Due to the reasons explained, it is not easy to achieve sensitive operation of busbar differential protection in low resistance grounded networks with generators directly connected to the main distribution bus.

C. Hybrid Grounding – Generators Connected Directly to the Main Distribution Bus

Hybrid grounding is elaborated in detail in [10]. Similar to the approach explained in Section III B., generators are connected directly to the main distribution bus. However, hybrid grounding represents an improvement to the conventional low resistance grounding method. One example of generators with hybrid grounded neutral connected directly to the main distribution bus is shown in Fig. 8.

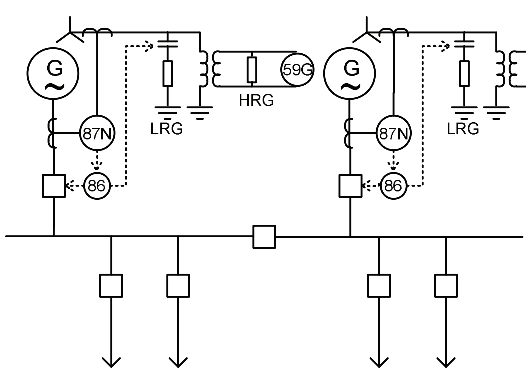

Fig. 8 Generators Direct Connection – Hybrid Grounding

Generators are equipped with sensitive ground differential protection 87N. In normal operation generators are grounded with parallel connection of low resistance ground and high resistance ground. The total impedance of the parallel connection is equivalent to low resistance. Low resistance is connected to the generator neutral via a contactor.

In case of a phase to ground fault on the power distribution bus, fault current will flow through the path of least resistance i.e., mainly through the low resistance path.

In case of a phase to ground fault in the generator, the generator ground differential protection will detect the fault and at the same time send a trip signal to the generator circuit breaker and an opening signal to the low resistance ground contactor. It is expected that the contactor will operate quickly and disconnect the low resistance path, effectively leaving the faulty generator grounded only through high resistance. When the generator circuit breaker opens after 3 to 5 cycles, the fault current will still flow from the faulted generator as long as the generator field remains excited while decaying gradually after excitation trip. After opening of the generator breaker, the fault will be limited by high resistance. Excitation decay is gradual under the control of the generator single line to ground short circuit time constant and it is expected to be in the range of 0.8–1.1 s [7].

When multiple hybrid grounded generator units are directly connected to the same bus, and when phase to ground fault occurs on one generator, it is necessary to take into consideration fault contribution from the other generators connected in parallel and from the system. The fault contribution from parallel generators will be limited by their own low resistance grounded paths and will last until the faulted generator breaker opens, typically 3 to 5 cycles of breaker clearing time in addition to one cycle of relay operating time. Even though the selection of higher limiting current of the low resistance ground in generator hybrid ground systems, such as 400 A or 800 A, will improve the dependability of bus differential relay operation, the selection of higher current limiting values has to be done with caution. When multiple generators operate in parallel, it is necessary to evaluate low resistance ground limiting current and keep it at the appropriate low level to avoid serious damage in the alternator in case of phase to ground faults.

In industrial power systems with on-site generation connected directly to the main distribution bus, hybrid grounding is an effective solution to help reduce alternator damage in case of internal generator phase to ground faults, and at the same time improve busbar differential protection dependability for busbar phase to ground faults.

IV. EXAMPLE OF HIGH IMPEDANCE BUSBAR DIFFERENTIAL PROTECTION SCHEME IMPLEMENTATION

A. Example Parameters of a Distribution System and Protection Scheme

An industrial plant with on-site generation and no connection to the Utility is built per IEC standards. The plant has the main power distribution system on the 11 kV voltage level. Multiple generator units are connected directly to the main distribution busbar, similar to the configuration presented in Section III B, Fig. 7. Each generator is equipped with low resistance grounding in the neutral to limit phase to ground fault currents to 100 A. Phase to ground fault current limit of 100 A on a single generator would achieve little damage in the alternator per Fig. 6 in Section III A in the worst case of a generator phase to ground fault with all generators connected in parallel.

The bus differential zone with the highest number of feeders has a total of 15 feeders which includes generator feeders, bus tie and outgoing feeders. The maximum symmetrical fault is assumed to be 50 kA, equal to the short circuit rating of the busbar.

One high impedance busbar differential protection relay is used to protect each bus differential zone. The busbar differential protection relay is connected in parallel with dedicated busbar differential protection current transformers with accuracy class PX [11], and CT magnetizing characteristic shown in Fig. 4.

Bus differential CTs have ratio N = 1600/1 A, knee point voltage V_{kn} = 424 V and CT internal resistance R_{ct} = 6 Ω. The maximum number of CTs in one bus differential zone is n = 15.

The busbar differential zone is required to remain stable for a maximum through fault I_{fmax} = 50 kA, which is assumed to be equal to the switchgear rating as the worst case. It is also required that the busbar differential protection is sensitive for the minimum in-zone fault. The minimum in zone fault will occur when only one generator is connected to the system and will be limited by the low resistance ground in the generator neutral to I_{fmin} = 100 A.

The longest CT lead resistance in the example is R_L = 0.5 Ω, varistor leakage current in the worst case is I_{res} = 15 mA. Internal resistance of the bus differential relay used in the scheme is R_{87B} = 4,375 Ω.

B. Relay Setting and Protection Security

When Equation (1) in Section II B is applied to find the minimum voltage setting required to ensure stability for out-zone faults, it is calculated that the setting voltage should satisfy the following condition: V_{set} > 50,000/1600 × (6 + 0.5) = 203.1 V.

From the options available in the bus differential relay, the voltage setting is selected to be: V_{set} = 210 V.

Since the CT knee point voltage is V_{kn} = 424 V, relay voltage setting threshold of 210 V will be firmly on the linear part of the CT magnetizing characteristic. From Equation (3) in Section II B, CT saturation factor will be equal to approximately k = 2, which is a recommended saturation factor by the relay manufacturer used in this example. Bus differential protection will be stable for the maximum possible out-zone fault and meets the requirement for protection security.

C. Relay Sensitivity and Protection Dependability

When the operating voltage equal to the setting voltage of 210 V is applied across the relay internal high resistance of 4,375 Ω, the relay operating current at setting voltage V_{set} is calculated to be I_r = 48 mA. When operating voltage equal to the setting voltage V_{set} of 210 V is plotted on the CT magnetizing characteristic shown in Fig. 4, magnetizing current at setting voltage V_{set} is I_m = 3.5 mA. As mentioned earlier in this section, the total number of CTs in the bus differential zone is n = 15, CT ratio is N = 1600/1 and varistor leakage current in the worst case is I_{res} = 15 mA.

From Equation (2) in Section II B, it is calculated that the primary sensitivity at voltage setting V_{set} will be equal to I_{opmin} = 184.8 A. The bus differential protection will not be sensitive for the minimum expected in-zone fault of 100 A, and the requirement for protection dependability is not satisfied.

D. Discussion of the Results

This example demonstrates that in low resistance grounded systems with generators directly connected to the main distribution bus, it may be challenging to meet the requirements to limit phase to ground fault currents in the generator and at the same time have dependable busbar differential protection for minimum in-zone faults.

In the example system, the high impedance busbar differential relay is stable for out-zone faults, but it is not sensitive for the minimum in-zone fault. The required sensitivity is not achieved even though the busbar differential protection CTs have fairly good characteristics. Busbar differential protection CTs have reasonably low CT ratio, low magnetizing current and high knee point voltage.

Using CTs with a lower primary rated current to lower the ratio N to increase sensitivity would not be advised since the CT primary rated current is selected based on the maximum expected load current on any feeder including generator and bus tie and this value is difficult to change. From Equation (2) in Section II B, it is clear that smaller CT magnetizing current would result in more sensitive pick-up threshold. To lower the magnetizing current, a larger core cross section would be required. A larger core cross section would require using longer conductors for the CT secondary winding and longer conductors would increase the CT resistance R_{ct} [5]. From Equation (1) and (3) in Section II B, higher internal CT resistance R_{ct} would also require a higher CT knee point voltage V_{kn}. Lowering the magnetizing current I_m and increasing the knee point voltage V_{kn} would increase the CT size and possibly create problems with CT installation due to space limitations in the switchgear.

V. OPTIONS TO IMPROVE SENSITIVITY OF BUSBAR PROTECTION SCHEMES

Besides replacing the CTs with ones that have better characteristics, other options can be explored to improve the sensitivity of the busbar protection.

A. High Impedance Busbar Differential Protection with Sensitive Ground Fault Protection

Sensitive ground fault relay 50SEF can be included in the busbar protection scheme to supplement the high impedance busbar differential protection 87B to achieve better sensitivity for phase to ground faults. One differential zone with high impedance differential and sensitive ground fault protection is shown in Fig. 9 as an example.

Sensitive earth fault relay 50SEF is installed in the neutral connection of the busbar differential protection relay circuit.

High impedance busbar differential relay 87B will clear high magnitude in-zone faults instantaneously and remain stable for high magnitude out-zone faults. The security of the high impedance differential relay protection is achieved by using

CTs with high knee point voltage and setting the relay according to the rules explained in Section II B.

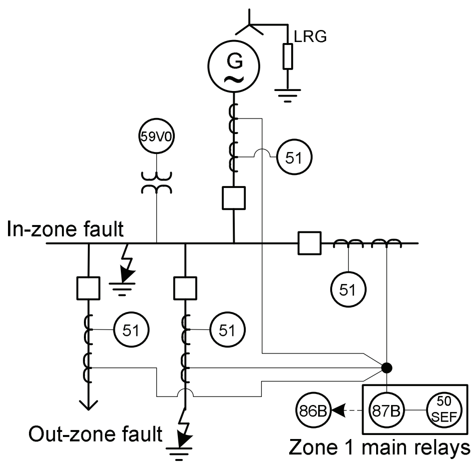

Fig. 9 High Impedance Bus Differential Protection Scheme with Sensitive Ground Fault Protection – CT Connections – One Zone Representation

Low magnitude in-zone faults that the high impedance busbar differential relay 87B cannot detect will be detected and cleared by the sensitive ground fault protection 50SEF. Sensitive ground fault protection 50SEF needs to be supervised to avoid false tripping due to unbalances in the differential circuit caused by high magnitude out-zone faults. To ensure security of the sensitive ground fault relay 50SEF, two methods can be used to supervise its operation:

1. Zero sequence overvoltage relay $59V_0$ is connected to the busbar VT. A zero sequence overvoltage relay will close the contact in the event of a ground fault to confirm that a ground fault has occurred.
2. Normally closed auxiliary contacts of overcurrent 51 relays of all feeders in the busbar differential zone are connected in series with trip contacts of 50SEF and $59V_0$. The auxiliary contacts of the 51 relays should open on overcurrent pick-up without time delay. The auxiliary contact of any 51 relay will open if the fault is an out-zone fault of a high magnitude that may create unbalance in the differential circuit and cause false operation of 50SEF. Opening the 51 contact will prevent 50SEF relay from tripping the busbar differential zone. The auxiliary contact of any 51 relay will also open if the fault is an in-zone fault of a high magnitude. The 50SEF relay will not trip the busbar differential zone for a high magnitude in-zone fault, but that is perfectly fine because 87B will trip.

The tripping schematic of the high impedance differential and sensitive ground fault protection scheme is shown in Fig. 10. Auxiliary control voltage of 110 VDC is used in the example schematic.

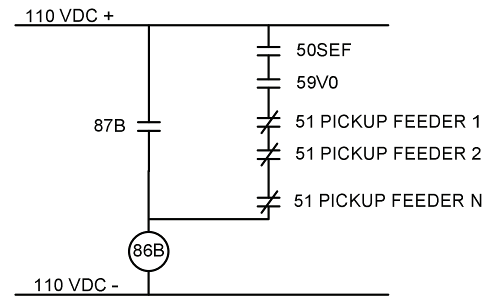

Fig. 10 Tripping Schematic of High Impedance Differential and Sensitive Ground Fault Busbar Protection Scheme

Sensitive ground fault 50SEF relay tripping and zero sequence overvoltage $59V_0$ relay tripping should be time delayed to allow the 51 relays to pickup, open contacts and block the 50SEF trip, if the condition for trip blocking exists. Delayed operation to clear phase to ground bus faults by 50SEF is acceptable to a certain extent because bus faults which the 50SEF relay is responsible for are low level limited faults. Faults of high magnitudes will be cleared instantaneously by high impedance bus differential protection 87B.

Functions 50SEF, $59V_0$ and 51 may be a part of multifunction relays e.g., feeder protection relays or motor protection relays. Multifunction relays may be used in the power distribution network to protect equipment other than the busbars. No additional relays may be required to obtain the functions required in busbar protection application described in this section. However, there may be a preference to use a separate dedicated 50SEF relay for busbar protection in tandem with the 87B relay. If the relay performing the $59V_0$ function measures the zero sequence voltage directly, it may be necessary to use a VT with an open delta secondary. In addition, it may be necessary to use an external resistor in the input of the high impedance bus differential protection relay 87B to improve stability, as described in the example that follows in this section.

The tripping scheme shown in Fig. 10 can be designed to use hardwiring of dry contacts from the relays used in the scheme, which adds complexity to the inter-cubicle wiring. Alternately, the tripping scheme can be designed to use communication signals, e.g., IEC 61850. When relays are already connected in a communication network, protective function statuses can be communicated between the relays and programmed into the trip logic to reduce or eliminate additional wiring in the busbar protection scheme.

The example explained in Section IV is used to demonstrate implementation of high impedance differential protection and sensitive ground fault protection. Three phase representation of the combined circuit is shown in Fig. 11. For simplicity, the CTs are represented only by their exciting impedances. Internal CT resistance, R_{ct}, and the resistance of 87B relay varistor are not shown.

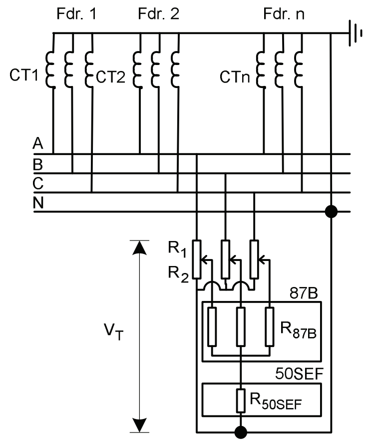

Fig. 11 Three Phase Connection of High Impedance Differential and Sensitive Ground Fault Busbar Protection

An adjustable resistor is wired in the inputs of the high impedance differential relay 87B. The total per-phase resistance of the adjustable resistor is $R_1 + R_2 = 3{,}296\ \Omega$. Partial resistances R_1 and R_2 selected in this example are $R_1 = 2{,}000\ \Omega$ and $R_2 = 1{,}296\ \Omega$. As mentioned in Section IV, internal resistance of the bus differential relay is $R_{87B} = 4{,}375\ \Omega$. Internal resistance of the sensitive ground fault relay is $R_{50SEF} = 48\ \Omega$. Voltages that develop across the 87B relay resistance and the 50SEF relay resistance are V_{87B} and V_{50SEF} respectively.

Single phase representation of the high impedance differential and sensitive ground fault busbar protection connection is shown in Fig. 12.

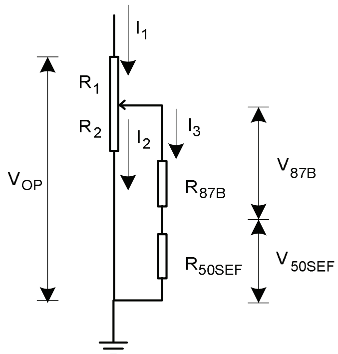

Fig. 12 Single Phase Representation of High Impedance Differential and Sensitive Ground Fault Busbar Protection

From Fig. 11, CT secondary imbalance current is:

$$I_1 = I_2 + I_3 \tag{4}$$

where

I_1	CT secondary imbalance current
I_2	bypass current
I_3	current through 87B and 50SEF relay, equal to V_{87B} / R_{87B} and V_{50SEF} / R_{50SEF}

Operating voltage of the differential scheme is:

$$V_{OP} = R_1 \times I_1 + R_2 \times I_2 \tag{5}$$

where

V_{OP}	operating voltage
R_1	adjustable resistor partial resistance R_1
I_1	CT secondary imbalance current
R_2	adjustable resistor partial resistance R_2
I_2	bypass current

Primary operating current of the bus differential protection and sensitive earth fault protection scheme is:

$$I_{op\min} = N \times (I_1 + n \times I_m + I_{res}) \tag{6}$$

where

I_{opmin}	minimum primary fault current that can be detected by busbar protection
N	bus differential protection CT ratio
I_1	CT secondary imbalance current
n	number of CTs connected in parallel in the bus differential zone
I_m	bus differential protection CT magnetizing current at operating voltage V_{OP}
I_{res}	leakage current of the varistor

For stability of the high impedance bus differential protection 87B during through faults, operating voltage V_{OP} on the bus differential protection circuit is selected to be equal to V_{OP} = 210 V, a value calculated for V_{set} in Section IV B. High impedance differential relay 87B setting voltage is selected as 70 V, a change from 210 V used in Section IV. To operate the relay 87B by exceeding the voltage V_{87B} = 70 V, and in turn exceeding the voltage V_{OP} = 210 V, from Equations (4) and (5), the CT secondary imbalance current needs to be at least I_1 = 0.07 A.

When operating voltage V_{OP} of 210V is plotted on the CT magnetizing characteristic shown in Fig. 4, the magnetizing current is I_m = 3.5 mA. The total number of CTs in the bus differential zone is n = 15, CT ratio is N = 1600/1 and varistor leakage current at 70 V setting of 87B relay is I_{res} = 15 mA.

From Equation (6), it is calculated that primary sensitivity of 87B relay at operating voltage V_{OP} = 210 V will be equal to I_{opmin} = 220 A.

Current trip setting of the sensitive ground fault relay 50SEF is selected as 0.0025 A. For the setting current equal to I_3 = 0.0025 A, voltage across 50SEF resistance R_{50SEF} will be V_{50SEF} = 0.12 V and voltage across 87B resistance R_{87B} will be V_{87B} = 10.94 V. Total voltage on partial resistance R_2 will be 11.06 V and the bypass current will be equal to I_2 = 0.009 A. From Equation (4), CT secondary imbalance current is I_1 = 0.011 A. Equation (5) gives operating voltage V_{OP} = 33.12 V.

When operating voltage V_{OP} of 33.12 V is plotted on the CT magnetizing characteristic shown in Fig. 4, magnetizing current is I_m = 1 mA. The total number of CTs in the bus differential zone is n = 15, CT ratio is N = 1600/1 and varistor leakage current at 10.94 V developed across 87B relay is I_{res} = 1 mA.

From Equation (6), it is calculated that the primary sensitivity of 50SEF relay for operating current 0.0025 A will be equal to I_{opmin} = 43.25 A.

The scheme will operate for phase to ground in-zone faults of 43.25 A and will provide sensitive and dependable operation for the minimum expected phase to ground busbar in-zone faults of 100 A. Sensitive earth fault relay 50SEF will clear low magnitude phase to ground in-zone faults between 43.25 A and 220 A with a time delay. High impedance differential relay will clear all in-zone faults higher than 220 A instantaneously.

The sensitivity of high impedance differential and sensitive ground fault busbar protection is 43.25 A, while the sensitivity of high impedance bus differential protection alone calculated in Section IV C is 184.4 A.

The high impedance differential and sensitive ground fault busbar protection scheme is acceptable since it has adequate sensitivity for in-zone faults and it is stable for out-zone faults.

B. Other Methods to Improve Bus Differential Protection Sensitivity

Other methods to improve bus differential protection sensitivity include selection of a different type of generator grounding. The sensitivity issue described in the example might have been resolved with the low resistance of a hybrid ground system, for example equal to 400 A, if the hybrid system low impedance limiting current of 400 A was proven suitable by analysis of alternator damage. As mentioned in Section III C, when multiple generators operate in parallel, it is necessary to evaluate the low resistance ground limiting current of the hybrid grounding system and verify the total fault current contribution and fault clearing time against the alternator damage curve.

Low impedance bus differential protection should also be considered in protection sensitivity evaluations [4]. In some applications low impedance bus differential protection may provide more sensitive operation than high impedance bus differential protection. Limiting factors in low impedance bus differential relay sensitivity may be the high CT ratio of some feeders such as a bus tie, or available minimum pickup setting in the relay. For some low impedance differential relay designs where summation CTs are used, the relay manufacturer may recommend the minimum fault pickup to be higher than the maximum load current in any feeder included in the low impedance bus differential protection zone, which may not provide adequate sensitivity.

Other non-differential bus protection methods may also be evaluated e.g., reverse zone blocking [3]. The sensitivity of a reverse zone blocking scheme also depends on the minimum available setting point of any overcurrent or ground overcurrent relay in the scheme. The high CT ratio which is typically used in a bus tie, impacts the sensitivity of the relay connected to it, and the sensitivity of the entire scheme. Reverse zone blocking is a time delayed scheme, which may not be desirable when high magnitude in-zone faults occur on the busbar.

VI. CONCLUSIONS

Bus differential protection in industrial plants should be planned in the early stages of the design by considering multiple factors. When generators are directly connected to the bus protected by bus differential protection, the choice of generator grounding will have a direct impact on the required busbar protection sensitivity. To ensure that bus differential protection is sensitive to detect minimum in-zone faults and stable for high magnitude out-zone faults, it is necessary to properly select components of the bus differential protection scheme. Current transformer parameters, type of protective relay, method of scheme supervision, etc. have a direct impact on the objectives of the protection scheme to ensure security and dependability. In some situations, conventional, readily available differential relays may not fully satisfy the protection scheme objectives and busbar differential scheme might require additional engineering. This paper discusses the importance of a coordinated approach in the selection of generator grounding and the selection of the bus differential protection. It also presents an example of how the sensitivity of a conventional differential protection can be improved.

VII. REFERENCES

[1] J. L. Blackburn, *Protective Relaying, Principles and Applications*, New York, NY: Marcel Dekker, Inc. 1987.

[2] W. A. Elmore, *Protective Relaying Theory and Applications*, New York, NY: Marcel Dekker, Inc. 1994.

[3] H. Kiank, W. Fruth, *Planning Guide for Power Distribution Plants: Design, Implementation and Operation of Industrial Networks*, Erlangen, Ger.: Publicis MCD Verlag 2011.

[4] K. Behrendt, D. Costello, S. E. Zocholl, "Considerations for Using High-Impedance or Low-Impedance Relays for Bus Differential Protection", *63rd Annual Conference for Protective Relay Engineers*, College Station, 2010.

[5] G. Ziegler, *Numerical Differential Protection Principles and Applications*, Erlangen, Ger.: Publicis MCD Verlag 2012.

[6] IEEE 142-2007, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*, New York, NY: IEEE.

[7] L. J. Powell, *The Impact of System Grounding Practices on Generator Fault Damage,* IEEE Transactions on Industry Applications, Vol. 34, pp. 923–927, Sept./Oct. 1998.

[8] ANSI/IEEE C37.101-2006, *IEEE Guide for Generator Ground Protection*, New York, NY: IEEE.

[9] ANSI/IEEE C37.102-2006, *IEEE Guide for AC Generator Protection*, New York, NY: IEEE.

[10] P. Pillai, B. G. Bailey, J. Bowen, G. Dalke, B. G. Douglas, J. Fischer, J. R. Jones, D. J. Love, C. J. Mozina, N. Nichols, C. Normand, L. Padden, A. Pierce, L. J. Powell, D. D. Shipp, N. T. Stringer, R. H. Young, *Grounding and Ground Fault Protection of Multiple Generator Installations on Medium-Voltage Industrial and Commercial Power Systems*, IEEE Transactions on Industry Applications, Vol. 40, No. 1, pp. 11–32, Jan./Feb. 2004.

[11] IEC 61869-2-2012, *Instrument Transformers - Part 2: Additional Requirements for Current Transformers*, Geneva, Switzerland: International Electrotechnical Commission, 2012.

VIII. VITA

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