EFFECTS OF PHASE IMPEDANCE IMBALANCE ON GROUND-FAULT PROTECTION RELIABILITY IN RING-BUS CONFIGURATIONS

This LFI(n) highlights that the relevant vulnerability is not a difference between the total impedance of the clockwise and counter-clockwise legs of a closed ring. The vulnerability arises when the A, B and C phase impedances are not sufficiently equal within the same leg. During a large transient, each phase divides around the ring differently, so the three phase currents within either leg may not vectorially sum to zero. Core-balance current transformers can interpret this temporary residual current as a ground fault, even though no current is flowing to ground.

Why this Learning Is Being Issued

A DP vessel experienced spurious opening of bus ties within its high-voltage ring when starting large consumers, including deck cranes. The recorded trip condition was ground fault. Investigation found no ground fault on the consumer being started or elsewhere on the bus.

The problem was eventually traced to small differences between the A, B and C phase impedances within the individual ring legs. These differences can arise naturally from cable geometry and routing, conductor arrangement, connections and terminations. A difference between the overall impedance of one leg and the other changes the division of load current around the ring but is not, by itself, the ground-fault protection problem described in this LFI(n).

During the starting transient, the phase currents divided between the clockwise and counter-clockwise paths in different proportions because the A, B and C impedances within each path were not identical. At an intermediate point in either leg, the local currents therefore did not satisfy Ia + Ib + Ic = 0. A core-balance current transformer, or a protection function deriving residual current by vectorially summing the outputs of three individual line current transformers, could detect this non-zero residual and interpret it as a ground fault. The imbalance disappeared when the two paths recombined at the feeder or fault location, where the complete phase currents again summed to zero.

The unwanted opening of bus ties altered the intended power-system configuration and could challenge the assumptions used to establish DP redundancy, protection selectivity and the worst-case failure design intent.

Central learning: In a closed ring, ground-fault protection security depends on phase-impedance balance within each individual leg, not merely on comparison of the total impedance of the clockwise and counter-clockwise routes. During large transients, Ia + Ib + Ic may be non-zero at an intermediate location in each leg even though no ground fault exists; the residual disappears where the paths recombine.

Target Audience for this Learning

- Charterers and their Project Teams.
- DP Vessel Owners & Operators / Management Teams.
- Vessel crew including Industrial Mission personnel.

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- Verification and assurance providers.
- Industry bodies / regulators.

What was learned?

The closed ring provided clockwise and counter-clockwise paths between the source and the starting consumer. Each phase current divided between these paths according to the impedance presented to that phase. The essential problem was not that one complete path had a different total impedance from the other. The problem was that the A, B and C impedances were not identical within the same path, so each phase split around the ring in a different proportion.

At an intermediate measuring point in the clockwise leg, the local phase currents could therefore produce $I_{a,cw} + I_{b,cw} + I_{c,cw} \neq 0$. The same could occur in the counter-clockwise leg: $I_{a,ccw} + I_{b,ccw} + I_{c,ccw} \neq 0$. These residual quantities were equal and complementary in the overall circuit and disappeared when the two paths recombined at the feeder or actual fault location. No zero-sequence current was flowing to ground.

How the Spurious Operation Developed

During the starting of a large consumer, the high phase currents divided around the ring. Because the three phase impedances within each leg were slightly different, the share of phase A current taking a leg differed from the shares of phase B and phase C current taking that same leg. The vector sum measured by a core-balance current transformer around that leg was therefore non-zero. The same effect could be seen where the protection derived residual current from the vector sum of three individual line current transformers. In either arrangement, the ground-fault element could pick up even though the insulation system was healthy. Appendix C illustrates the current-splitting mechanism, the non-zero local residual at intermediate protection locations, the cancellation where the paths recombine, and the two alternative residual-current measurement arrangements.

When the clockwise and counter-clockwise contributions recombined at the feeder, the apparent residual cancelled and Ia + Ib + Ic returned to zero. The location of the core-balance current transformers within the separated ring paths was therefore critical. A balanced steady-state load-flow assessment or comparison of total leg impedances alone would not reveal this vulnerability.

Protection Study and Assurance Implications

The protection assessment should establish the A, B and C impedance of each individual ring leg, including cable geometry, conductor arrangement, phase transposition where applicable, busbar sections, joints, terminations and connection impedance. The analysis should calculate the phase-current split and the resulting residual current at each protection location, including both core-balance current transformers and residual-current functions formed by summing three individual line-current-transformer inputs.

The assessment should include the largest credible balanced transients, including deck-crane starting, large motor starting and transformer energisation, for all intended generator and bus-tie combinations. The calculated or measured quantity of interest is the local residual 3I0 = Ia + Ib + Ic at each protection location before the two ring-path currents recombine.

Protection settings and logic should be demonstrated for the full range of intended configurations. Successful operation in a split-ring or linear-bus arrangement does not demonstrate satisfactory performance in a closed ring.

Potential Mitigation for Ground-Fault Elements

In some installations, unwanted ground-fault operation may be addressed by setting the residual-current element above the maximum credible non-fault residual produced by phase-impedance imbalance and large load transients. This requires quantified evidence of the maximum local Ia + Ib + Ic at each residual-current protection location, whether measured directly by a core-balance current transformer or derived from three individual line current transformers, together with suitable allowance for ratio error, phase-angle error, saturation, wiring and relay measurement performance.

Protection security may also be improved by combining residual-current detection with an independent indication of a genuine ground fault, such as a neutral overvoltage excursion. Neutral overvoltage supervision can help distinguish genuine zero-sequence voltage displacement from the temporary local

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residual current created while balanced phase currents split unequally around the ring.

Any reduction in sensitivity, increase in pickup threshold or additional delay should be justified by study. A setting change that prevents spurious operation may also reduce sensitivity to high-impedance or developing ground faults. The revised philosophy should demonstrate acceptable security, sensitivity, selectivity and operating time.

Split-Ring Operation as an Operational Mitigation

Operating the system as a split ring can remove the parallel clockwise and counter-clockwise current paths and may therefore prevent the false residual-current mechanism described in this LFI(n). Split-ring operation is an operational mitigation rather than a correction of the underlying phase-impedance imbalance or protection design.

Care is required when selecting and changing the position of the split. A generator, or another source demonstrated as suitable by the approved power-system design, should remain connected to the energised bus sections on both sides of the split. Moving the open bus tie without coordinating generator connection can leave a section without an appropriate source, create an unintended dependency, or invalidate the DP redundancy and worst-case failure assumptions.

The preferred split position may change with the operating mode, connected mission equipment, thruster allocation, generator commitment and maintenance status. Where several split positions are permitted, a Thruster and Generator Operating Strategy (TAGOS), or equivalent controlled operating instruction, may be used to define the required generator and bus-tie configuration. The TAGOS should require the necessary generator allocation to move with the split and should identify the permitted sequence for transferring the split position without creating an unacceptable transitional configuration.

Split-ring operating arrangements should be supported by the DP FMEA, protection study, power-system analysis and proving trials. The arrangements should also be reflected in operating procedures and the applicable A(W)SOG, including any restrictions on changing the split while conducting critical DP operations.

Limitations of the Mitigation

Ground-fault sensitivity changes or neutral overvoltage supervision may improve security against this specific false residual-current mechanism. They do not correct the underlying A, B and C impedance imbalance within a ring leg, and they may not resolve poor selectivity or unwanted operation associated with directional phase-overcurrent protection.

Directional phase elements respond to phase-current magnitude and direction rather than solely to Ia + Ib + Ic. Their performance may therefore remain influenced by current division, polarising quantities during transients, current-transformer performance, generator combination, short-circuit level, directional characteristic angles and changes in ring status.

Correcting the ground-fault element should therefore not be taken as evidence that the directional phase-overcurrent protection is stable and selective for all intended ring-bus configurations.

Suggested Action

Vessel owners, operators and DP assurance stakeholders should review ring-bus protection for

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sensitivity to actual installed impedance asymmetry and large-consumer transients. Actions may include:

1. *Reviewing ground-fault pickup, time delay, residual-current measurement and neutral overvoltage supervision.*
2. *Separately assessing directional phase-overcurrent elements, including polarising methods and characteristic angles.*
3. *Modelling actual phase and path impedances for every intended ring and bus-tie configuration.*
4. *Testing or otherwise validating protection stability during representative large-consumer starting and energisation transients.*
5. *Confirming that protection operation and the resulting network configuration remain consistent with the DP worst-case failure design intent.*
6. *Applying operational restrictions, revised starting arrangements, split-ring operation or protection redesign where reliable closed-ring selectivity cannot be demonstrated.*
7. Where split-ring operation is used as mitigation, confirming that suitable generation remains connected to the energised bus sections on both sides of the split.
8. Using a TAGOS or equivalent controlled operating instruction where the split position may move, so that generator allocation, bus-tie status and the sequence for transferring the split remain consistent with the approved DP operating philosophy.

Conclusions

The protection vulnerability was caused by differences between the A, B and C impedances within an individual ring leg. During a large transient, the phase currents split around the ring in different proportions, so Ia + Ib + Ic was non-zero at intermediate protection locations even though no current flowed to ground. The effect could be detected directly by a core-balance current transformer or derived by summing the outputs of three individual line current transformers.

The apparent residual current existed only while the clockwise and counter-clockwise phase-current contributions were separated. The imbalance disappeared where the two paths recombined at the feeder or fault location. Ground-fault sensitivity changes or neutral overvoltage supervision may improve security, but any change must preserve sensitivity to genuine ground faults.

Protection studies and testing should therefore determine the phase-by-phase impedance of each ring leg, calculate or measure local 3I0 during the largest credible transients, and demonstrate that each ground-fault element remains secure without compromising required fault sensitivity and selectivity.

Split-ring operation may avoid the parallel-path mechanism, but it should only be adopted within an approved operating philosophy that preserves suitable generation on both sides of the split and controls any movement of the split position, for example through a TAGOS.

APPENDIX C - Local Residual Current in a Closed Ring and Alternative CT Arrangements

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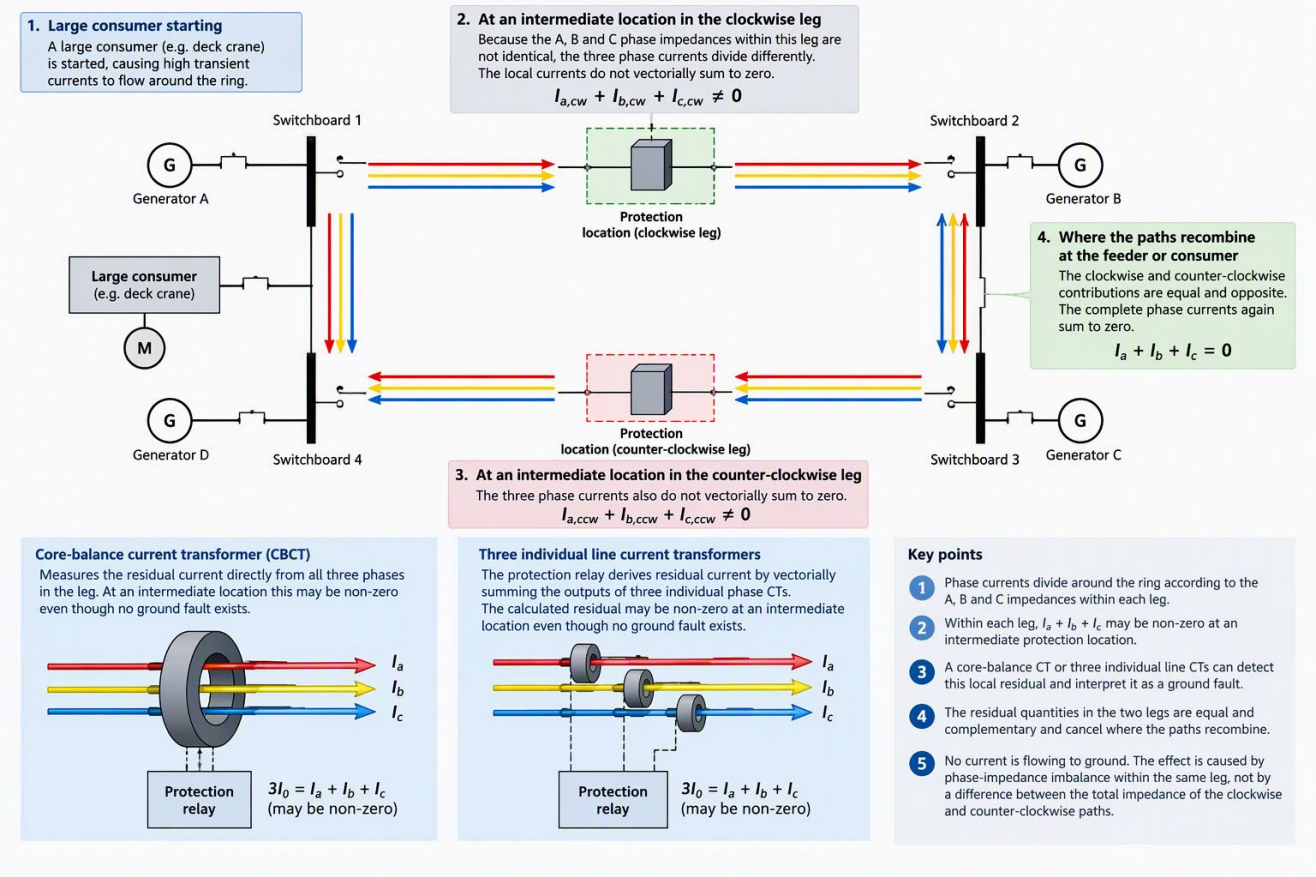

Figure C-1. Phase-impedance imbalance can produce a non-zero local residual current at intermediate locations in each ring leg. The residual may be measured by a core-balance CT or derived from three individual line CTs, and cancels where the clockwise and counter-clockwise paths recombine.

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