OPEN OR CLOSED RING NETWORKS?

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ABSTRACT

Open ring networks have been commonly used; they have been protected either with phase and earth simple or directional overcurrent protection relays.
The biggest drawback of open ring electrical power networks is that a line/cable fault will disconnect the customers that are connected downstream from that fault location until manual or automatic reconfiguration of the network is done.
How could we improve the System Average Interruption Frequency Index (SAIFI) and the System Average Interruption Duration Index (SAIDI)?
I.e. how to reduce the number and duration of power interruptions?
What if, we create a closed ring electrical power network?
Is there any impact of Distributed Generation?
Are there some protection principles that could help?
Note: this paper focuses on:
•The IEC world (three phase balanced networks) and
•On medium size ring networks such as for

- *Sensitive buildings*
- *Data centres*
- *Heavy industries (mainly cable based)*
- *Microgrid not connected to utility (yet)*

This paper does not fit for:
•Utility networks
•Isolated neutral earthing networks.

INTRODUCTION

Protection principles:

Directional over current protection blocking scheme basics:
Directional over current protection blocking schemes are based on, measurement of currents and voltages (fed from well sized instrument transformers), time discrimination principle and on the exchange of blocking signals via dedicated communication links. Thanks to the voltage, the direction of the power flow can be known. When an overcurrent is detected in the protected area, it instantaneously sends a blocking signal to the upstream protection (or "behind"* it), then after a certain time, if not blocked by the downstream protection (or "in front of"*), trips its breaker. Directional over current protection may have some limitation for some specific cases.
*:"upstream" and "downstream" do not exist in closed ring.

For this paper, the below definitions are used:

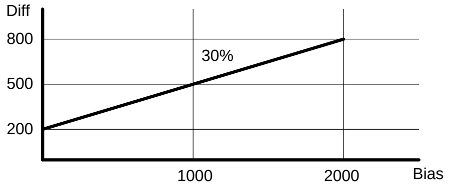
A directional protection is drawn as ◁ or △ or ▷ or ▽ with:

[Protected area (downstream or "in front of"*)] ◁ [Blocked area (upstream or "behind"*)]

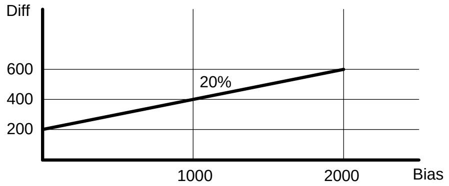
Differential protection basics:
A Differential protection scheme is based on measurement of current only (fed from well sized current transformers) and on the exchange of these measurements via dedicated communication links. Differential protections calculate the difference between the currents entering and leaving the protected zone. The protections operate when this difference exceeds a set threshold which depends on the flow of the current (biased characteristic).
Usually:

- The bias current is the sum of the current measured on each end divided by 2, even for "multi-ended" lines (more than 2 ends).
- The differential current is the difference of the current measured on each end (not divided by 2).
- Until twice the nominal current, the tripping area is the zone above the first slope.
- That slope starts from a minimum threshold, typically 20% of the nominal.

Example of 30% slope with 1000A nominal



Example of 20% slope with 1000A nominal



For this paper, the below definitions are used:

A differential protection is drawn as ◁ or △ or ▷ or ▽ with:

[Outside area] ▷ [Protected area] ◁ [Outside area]

Faults basics:

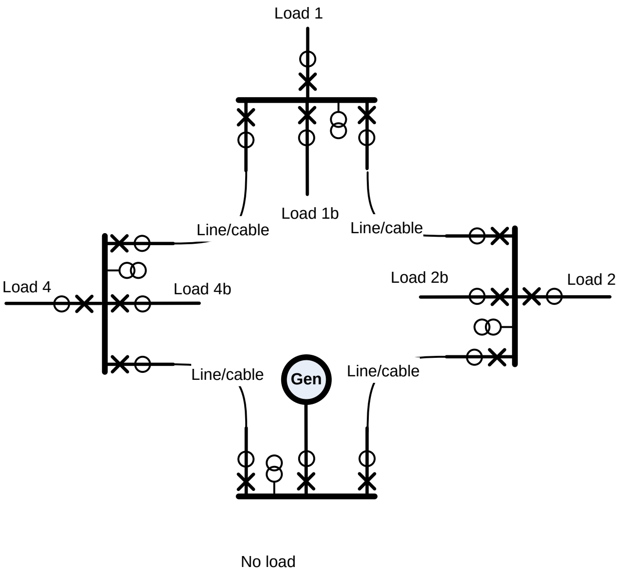
If a cable fault starts from phase to phase, it generally evolves quickly to phase to earth

If a line fault starts from phase to phase, it may or may not evolve to phase to earth

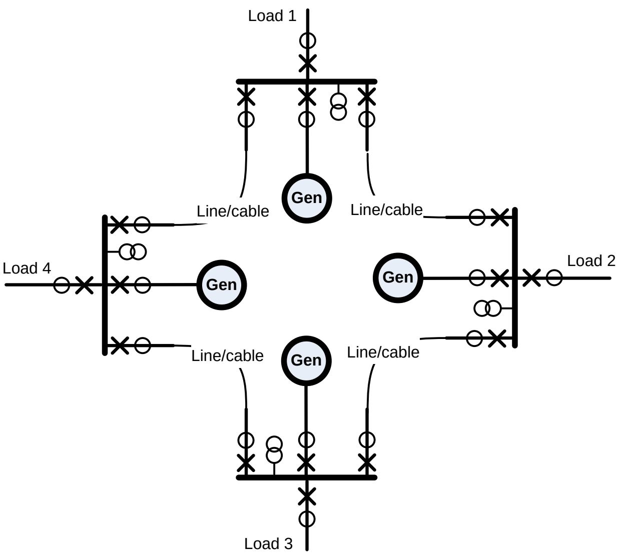
For the purpose to ease the different points of this paper:

The examples are based on ring networks with centralized generation (one set of generation (not mixed with any load) and distributed generation (four sets of a mix of generation and load linked to each other) with short cables or lines.

Centralized generation:



Distributed generation:



A "Gen" can be:

- A conventional synchronous generator only (i.e. no power electronics) or
- A utility connection, and, in that case Grid codes must be followed i.e. most commonly: no mix of load and generation at the same location.
- The busbar protection and the generator protection are not treated in this paper but depending on the voltage and power, it is highly recommended to have dedicated busbar and generator protections.
- We will focus on a fault that may occur on a line or a cable only as the Generator and busbar faults are protected with the above mentioned differential protections.

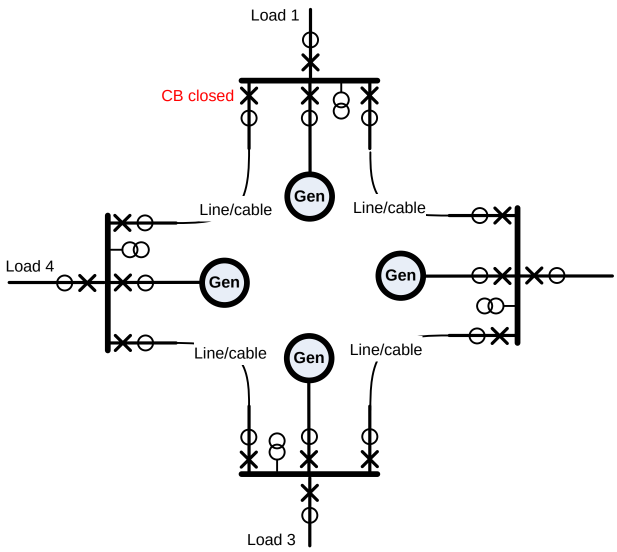
One solution to improve the SAIFI and the SAIDI i.e. to reduce the number and duration of power interruptions is to create a closed ring electrical power network

What happens if we use the same protection principles as for open ring power networks?

CLOSED RING:

<u>Loads and fault currents:</u>

Distributed generation:



Notes: or represent closed CBs and "Gen" can be in service or not.

- The maximum closed ring possible cable/line load happens when only the connected feeder is closed (for example CB1closed and CB2, CB3 and CB4 are open) and fed by the three other generators. It is around the sum of the opposite GenMaxLoad/2 + the biggest of the 2 other GenMaxLoad, i.e. if the generation capacity is of the same power around 1.5x GenMaxLoad.
- This is half of the maximum open ring possible cable/line load which is 3x GenMaxLoad
- The maximum possible cable/line phase-phase short circuit of a line is:

  If the generation phase-phase short circuit capacities are of different powers:

  For any line/cable (with similar impedances), it varies from the smallest of the adjacent GenMaxPhPhSC to the sum of all generators (Gen1MaxPhPhSC + Gen2MaxPhPhSC + Gen3MaxPhPhSC + Gen4MaxPhPhSC)/2 and

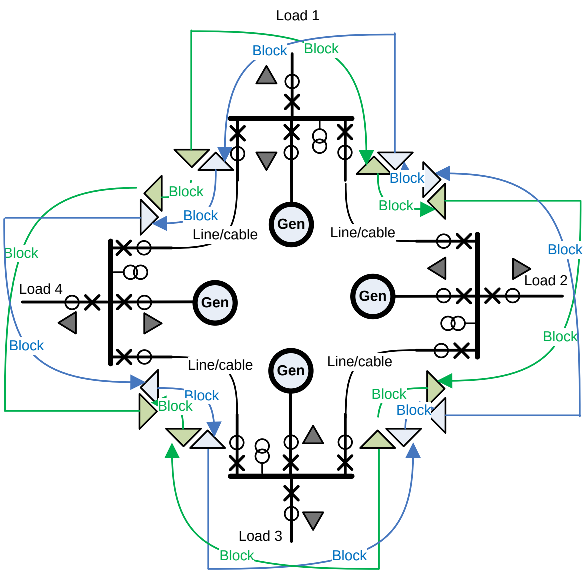
depends on the number of generator connected to the ring.
In the case of the same generation characteristic:
For any line/cable, it varies from GenMaxPhPhSC to 2x GenMaxPhPhSC

- This is half of the maximum open ring possible cable/line phase-phase short circuit capacities which is 4x GenMaxLoad
- The maximum phase-earth short circuit of a line/cable is the maximum short circuit limited by the earthing resistance which is constant whatever the number of generators and wherever it is connected.

For distributed generation, it is therefore, most of the time, impossible to set the phase-phase directional over current threshold above the biggest maximum load and below the smallest short-circuit that meets all possible configurations.
The closed ring does not require higher rated primary equipments (cables, circuit breakers) than for open rings and on the opposite reduces the stress on these equipments during faults.

Directional overcurrent based blocking scheme

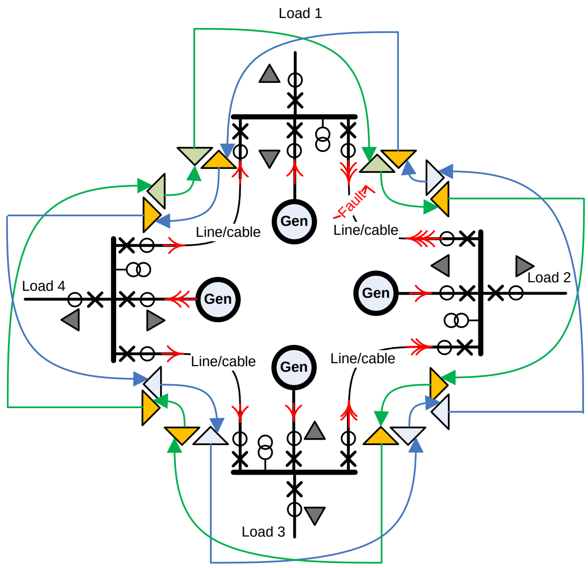
Principle:



Line or cable fault example:
For a fault (phase-phase or phase-earth) that occurs on a line/cable, the following scenario arises:

Detection of the fault:

Fault on 1/2 cable:

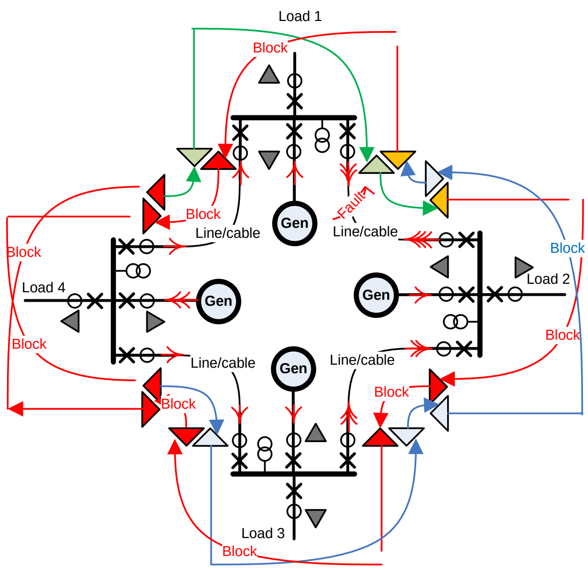


For some phase-phase faults (see 2.1) and all earth faults, the relays in orange “quickly” detect the fault and

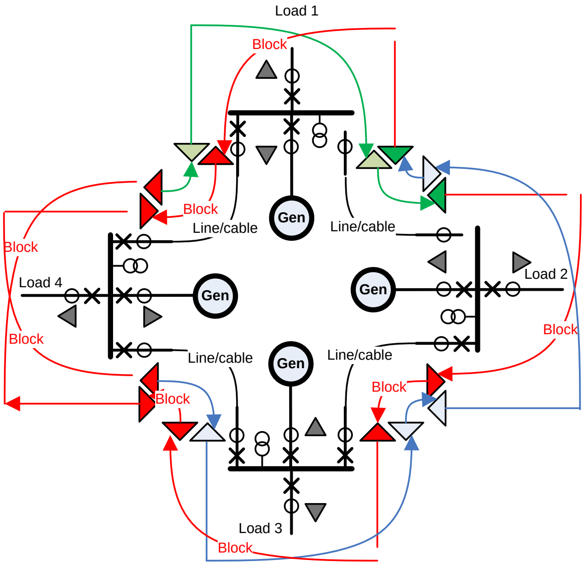
- Send the blocking signal to the relays behind them,
- Start their common delayed tripping timer

Blocking of the “behind” relays
The relays in red receive the blocking signal and stop their delayed tripping timer (thus will not trip)

Fault on 1/2 cable:



Delayed trip of the faulty line or cable
The relays in green, once their common delayed tripping timer as been reached, trip their associated breaker and **the fault is cleared without any loss of, neither generation, nor load**.



First findings:

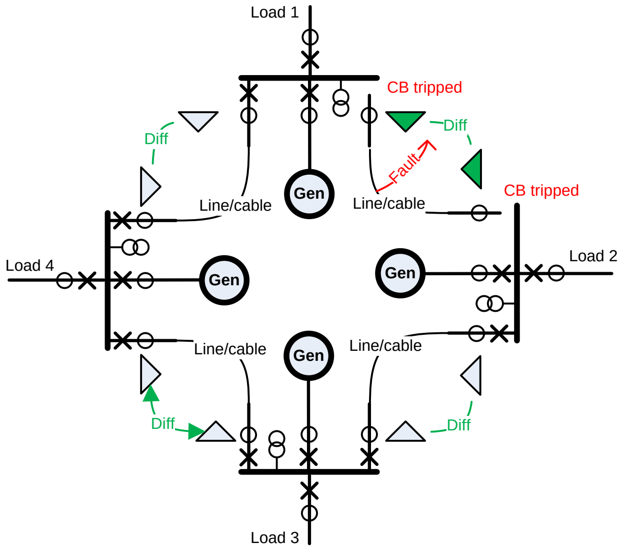
- Directional over current blocking scheme shall work for phase-earth faults but
- For distributed generation, directional over current blocking scheme works only for phase-phase faults that are always bigger than the variable maximum load current knowing that the fault current is as well variable as it depends on the availability of the generation. In other words: shall not be used to protect phase-phase fault in DG.
- On fault clearance, as there is no generation or load interruption SAIFI/SAIDI is very good.

Can we use differential protection?

Differential protection scheme:

For a phase-phase fault that occurs on a line, the following scenario arises:
Line or cable fault example:
Detection of the fault and instantaneous trip

Fault on 1/2 cable: 



Because of CT measurement "inaccuracy", the Differential characteristic is biased and line differential scheme is not sensible enough to detect small phase-earth faults:
Thus a resistive internal fault of Irf magnitude will be fully counted in "Diff" but only counted half in "Bias":
Pre-fault:

- Bias = (load + load) / 2 = load
- Diff = load – load = 0

Internal resistive fault:

- Bias = (Iload + Irf + Iload) / 2 = Iload + Irf/2
- Diff = Iload + Irf - Iload) = Irf

To be in the tripping area, the minimum Irf must be above the minimum threshold + X% of the bias i.e. Irf > 20% of nominal + X% of Bias (= Iload + Irf/2) so at nominal load:
Irf > 20% load + X% (load + Irf/2) i.e. Irf (1-X%/2) > (20%+X%) load thus
Irf > ((20%+X%)/(1-X%/2)) load
Example for X% = 30% then Irf = 0.5/0.85 load = 58.8% of nominal load which is not low
Example for X% = 20% then Irf = 0.4/0.9 load = 44.4% of nominal load which is better but not that low. For a phase-earth fault that occurs on a line or a cable, a Directional over current earth fault protection relays shall detect the earth fault and trip as described in chapter 2.

Second finding:

- Differential schemes trips without any delay (compared to blocking schemes).
- Differential scheme does works for phase-phase fault
- Differential scheme does not work for small phase-earth fault

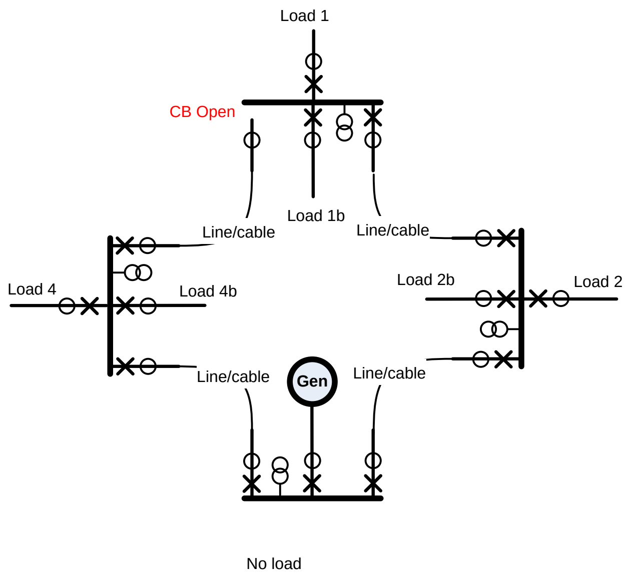
When the closed ring is tripped, it is used as open ring; are the above protection schemes still working?

Open ring:

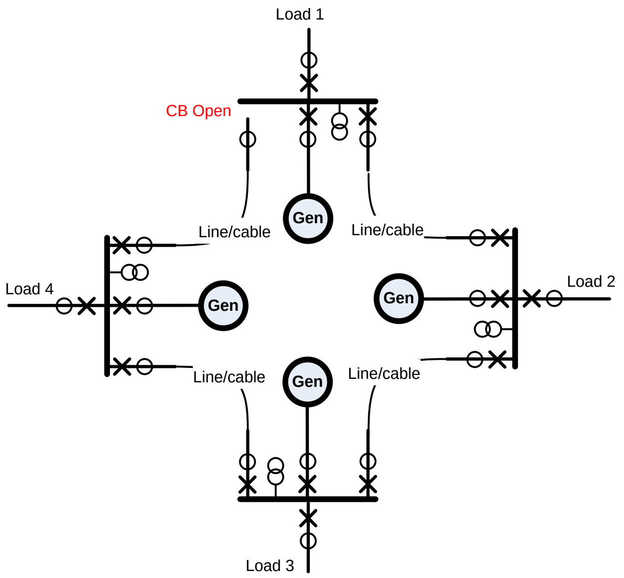
Loads and fault currents:

Differences between centralized and distributed generation:

Centralized generation



Distributed generation



There is an important difference on the maximum possible line/cable load and the maximum possible line/cable phase-phase short circuit of a line/cable between centralized and distributed generation:

For the centralized conventional synchronous generation/utility connection:

- The maximum possible line/cable load is the maximum generation of the unique centralized generation called here GenMaxLoad
- The maximum possible line/cable phase-phase short circuit is the maximum short circuit generated by the unique centralized generation called here GenMaxPhPhSC which does not vary much. For a conventional synchronous generator it is in the range of 2 to 4 nominal load with a high DC component.
- The maximum possible line/cable phase-earth short circuit is the maximum short circuit limited by the earthing resistance which is constant.

It is therefore easy to set the phase-phase directional over current threshold above the maximum load and below the phase-phase short-circuit and the earth fault directional over current threshold below the known earth fault current.

For the distributed generation:

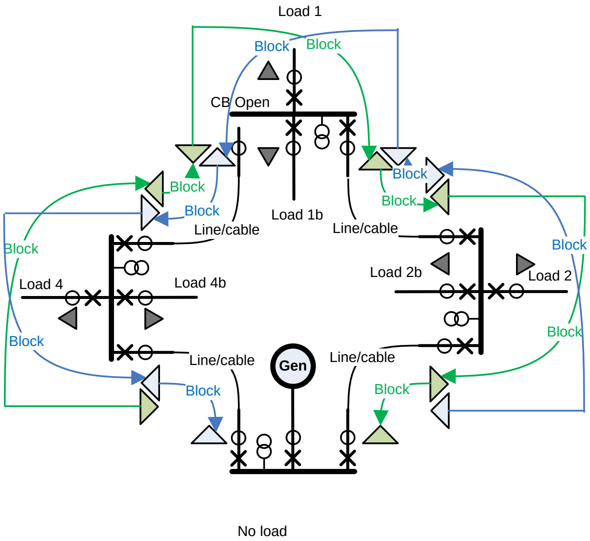
- The maximum possible line/cable load is:
  If the generation capacities are of different powers:
  For the top-right it is the biggest of Gen1MaxLoad (not feeding load 1) and the sum of Gen2MaxLoad + Gen3MaxLoad + Gen4MaxLoad (feeding load 1 only).
  For the bottom-right it is the biggest of the sum of Gen1MaxLoad + Gen2MaxLoad and the sum of Gen3MaxLoad + Gen4MaxLoad
  For the bottom-left it is the biggest of the sum of Gen1MaxLoad + Gen2MaxLoad + Gen3MaxLoad (feeding load 4 only) and Gen4MaxLoad (not feeding load 4)
  For the top-left it is 0 as it the open point
  In the case of the same generation capacity:
  For the top-right, the maximum possible line/cable load is 3x GenMaxLoad
  For the bottom-right, the maximum possible line/cable load is 2x GenMaxLoad
  For the bottom-left, the maximum possible line/cable load is 3x GenMaxLoad
  For the top-left, the maximum possible line/cable load is 0.
- The maximum possible line/cable phase-phase short circuit is:
  If the generation phase-phase short circuit capacities are of different powers:
  For any line/cable, it varies from the smallest of the adjacent GenMaxPhPhSC to the sum of all the generators (Gen1MaxPhPhSC + Gen2MaxPhPhSC + Gen3MaxPhPhSC + Gen4MaxPhPhSC)
  In the case of the same generation characteristic:
  For any line/cable, it varies from GenMaxPhPhSC to 4x GenMaxPhPhSC
- The maximum phase-earth short circuit of a line/cable is the maximum short circuit limited by the earthing resistance which is either constant whatever the number of generators or linear with the number of generators.

As for when the ring is closed, it is, most of the time, impossible to set the phase-phase directional over current threshold above the biggest variable maximum load and below the smallest variable short-circuit as both depend

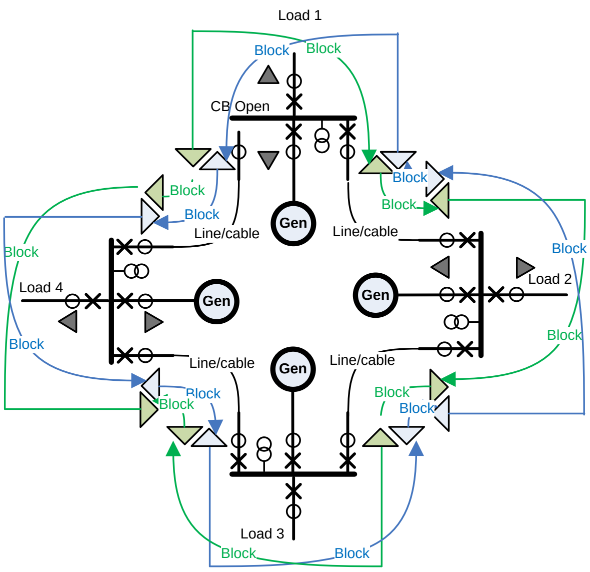
on which and how many generators are connected as well as how much power they each deliver.
The earthing location does not affect the blocking scheme.
Is the blocking principle still working?

Directional overcurrent based blocking scheme

Principle:
Centralized generation



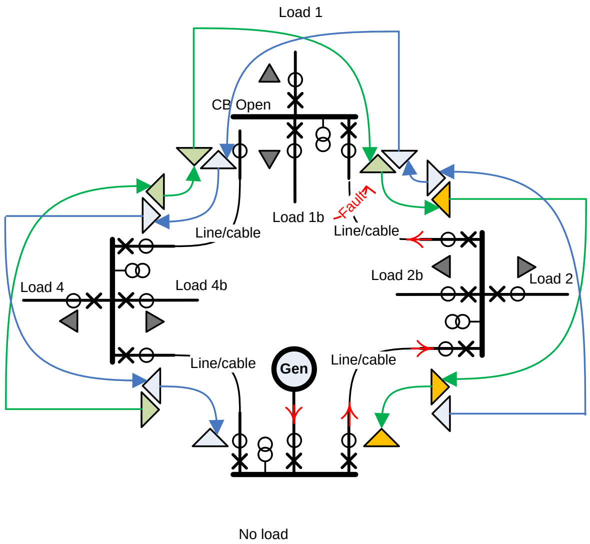
Distributed generation



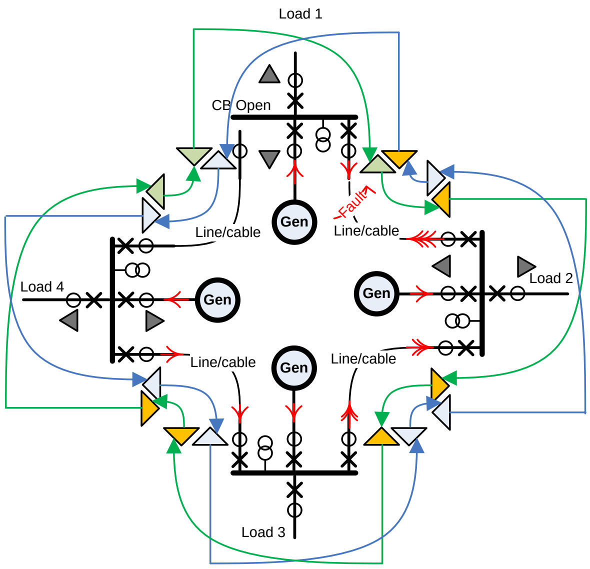
Line or cable fault example:
For a phase-phase or phase-earth fault that occurs on a line/cable, the following scenario arises:
Detection of the fault:

Fault on 1/2 cable: 

GenmaxPhPhSC > GenMaxLoad



Only in case of GenmaxPhPhSC > 3x GenMaxLoad**

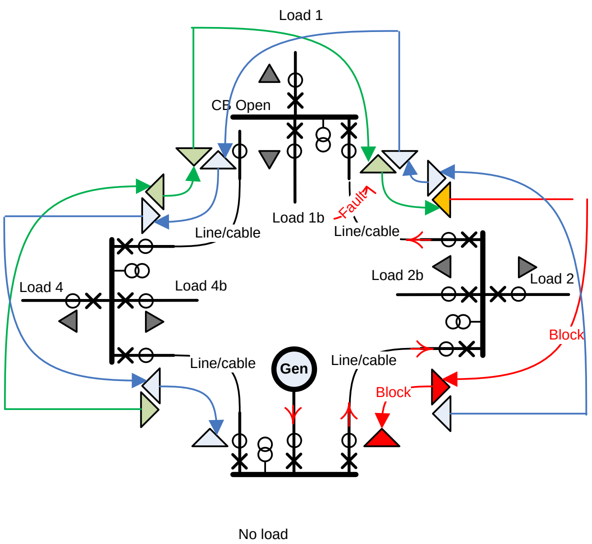


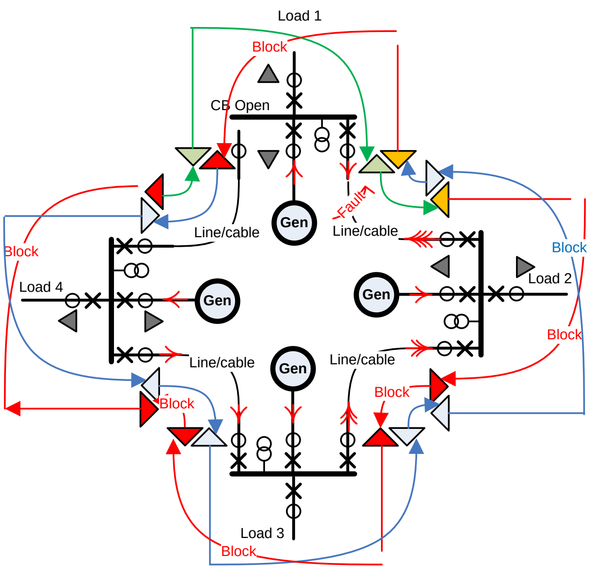
**: As each generator adds it own fault current contribution, the fault current is the highest in the bottom CT of the top-right corner then less at the bottom-right corner and the smallest is at the bottom-left corner. Thus, further the fault is, less chance the protection will have to pick-up but it does not affect the protection schemes (see 1.3.2).
The relays in orange "quickly" detect the fault and

- Send the blocking signal to the upstream relays,
- Start their delayed tripping timer (which is common for distributed generation case)

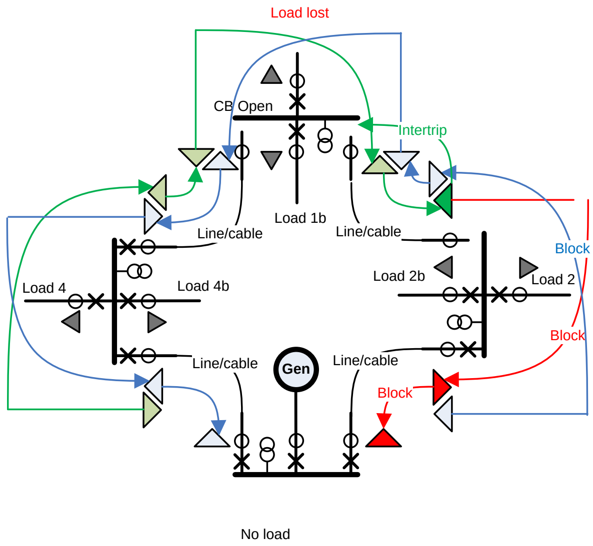
Blocking of the upstream relays
The relays in red receive the blocking signal and stop their delayed tripping timer (thus will not trip)

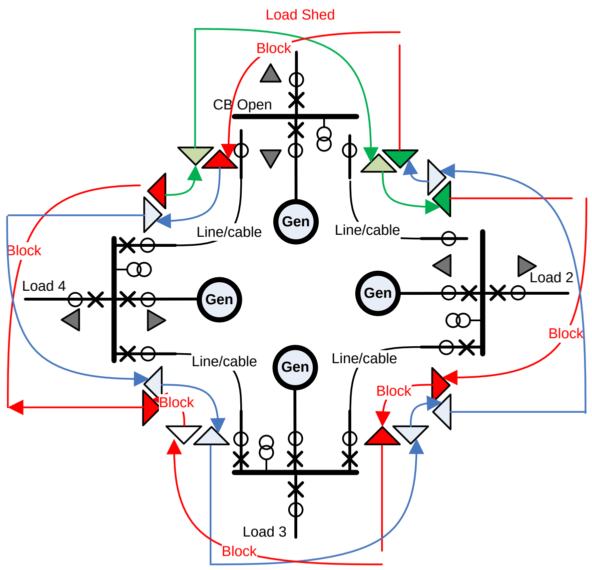
Fault on 1/2 cable: Fault



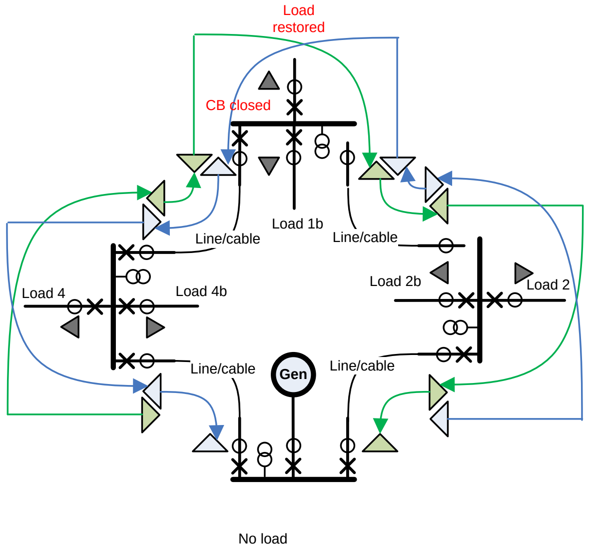


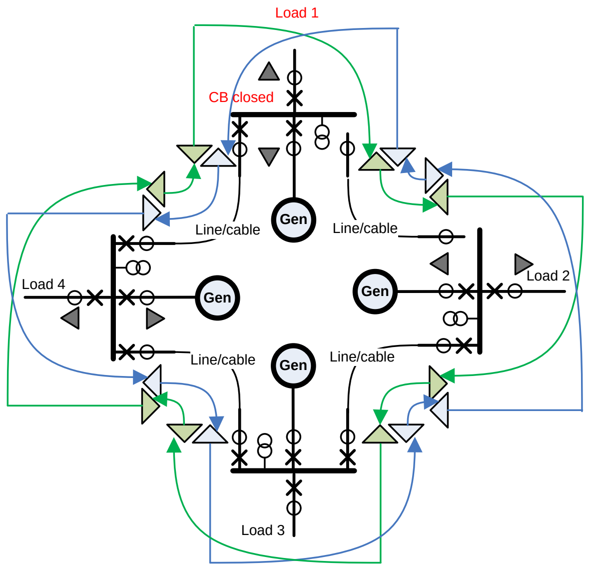
Delayed trip of the faulty line/cable
The relays in green, once their common delayed tripping timer as been reached, trip their associated breaker and the fault is cleared but the downstream load is, for the centralized generation, lost and for the distributed generation, at best, kept as is or shed, but not totally lost.





Closing of the normally open breaker
This closing operation is either manual or automatic and restores the full power to all loads.





Third findings:

- The closed ring protection schemes still work for open ring:

  Line/cable phase-earth faults are still detected for both kinds of generations.

  Line/cable phase-phase faults are still detected in centralized generation but only in some cases for distributed generation. In that case non tripping would result in damage of primary equipments that would strongly degrades further the SAIFI/SAIDI

- Fault clearance is slowed down by the delayed tripping timer(s)
- On fault clearance a load maybe lost or shed and thus degrades the SAIFI/SAIDI.

CONCLUSIONS

On the electrical power network:

- For closed ring centralized generation (and when grid code allows it) and distributed generation:
  The biggest benefit of closed rings is to continue to provide nominal power in case of a line or cable fault and thus a line or cable fault will not degrade the SAIFI/SAIDI.
  The closed ring does not require higher rated primary equipments (cables, circuit breakers) than for open ring and on the opposite reduces the stress on these equipments as load and fault will be divided by around 2. Consequently, circuit-breakers such as those used in secondary distribution [1], [2], are perfectly adapted to this closed ring scheme.
  Both Current transformers and Voltage transformers shall be used by the below protection scheme.
- When used as open ring:
  Some loads can be lost or shed and SAIFI/SAIDI will be affected by line or cable faults.

On the protection schemes:

- For closed ring distributed generation networks:
  Phase-phase directional overcurrent does not always work and differential schemes shall be used instead.
  Differential scheme does not work for small phase-earth fault and phase-earth directional over current shall be used instead.
  When used as open ring, the closed ring protection scheme still works.
- Differential relays detect phase-phase faults and trip faster than directional overcurrent relays, which is important to save the primary equipments or for safety reasons but do not detect "small" earth faults.
- Directional earth fault relays react with some delay on small fault currents; that may be good enough as primary equipments may not be too much stressed for such faults.
- Most of line differential numerical relays embed directional earth fault protection that uses the same communication channel.

The optimum is to operate sensitive power networks as closed ring protected by a scheme based on line differential relays embedding earth directional overcurrent blocking schemes that will still work when used as open ring.

About the author

Henri Grasset is an Automation Intelligent Electronic Device Expert at Schneider Energy Division. He holds an engineering degree from the Ecole Centrale de Nantes in France. He has worked in the Protection and Control domain since 1999.

REFERENCES

[1] Canpeng Ma (2012) ”Innovative MV switchgear for today’s applications” *CICED 2012 Paper FP0112*
[1] Jean-Marc Biasse (2009) ”Circuit-breaker RMU improves MV/LV transformer protection” *CIRED 2009 Paper 0320*