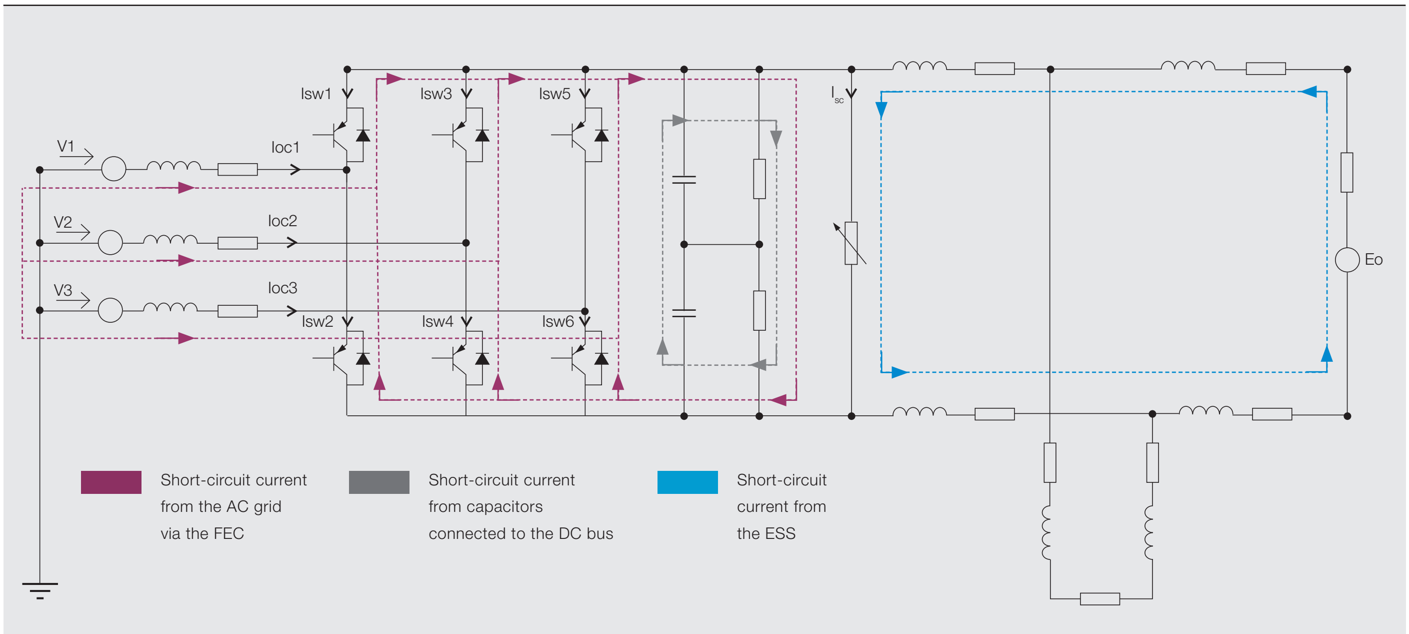
# Protect and survive

## Fault protection analysis in low-voltage DC microgrids with photovoltaic generators

MARCO CARMINATI, ENRICO RAGAINI – The connection of renewable-energy-based microgrids to national power grids has many advantages. However, care has to be taken when linking these two quite different electrical worlds to make sure that fault conditions are appropriately handled – in particular when a microgrid that includes a photovoltaic (PV) installation or an energy storage system (ESS) is connected to the grid by means of a front-end converter (FEC). This configuration can allow fault currents from the AC grid to pass straight through the converter, thus further exacerbating the fault. Most general-purpose FECs are based on insulated-gate bipolar transistors (IGBTs) combined with freewheeling diodes and are not able to interrupt fault currents in all situations. Therefore, a specific protection system is needed to ensure fault clearance and safety, especially when ESSs or DC generators are involved.

1 Short-circuit current components with an ESS




The connection to AC systems of low-voltage direct current (LVDC) microgrids that include PV plants is a topic that is becoming very relevant as ever more renewable power is fed into national grids. Apart from the usual electrical considerations of connecting these two worlds, thought also has to be given to how to deal with fault conditions as, depending on the different possible grounding schemes, PV plants and ESSs and their related electronics can behave in different ways during faults and thus have different consequences for grid operation and fault behavior.

In an LVDC microgrid, the DC section is typically separated from the AC grid by an FEC that feeds any surplus microgrid power into the AC grid.

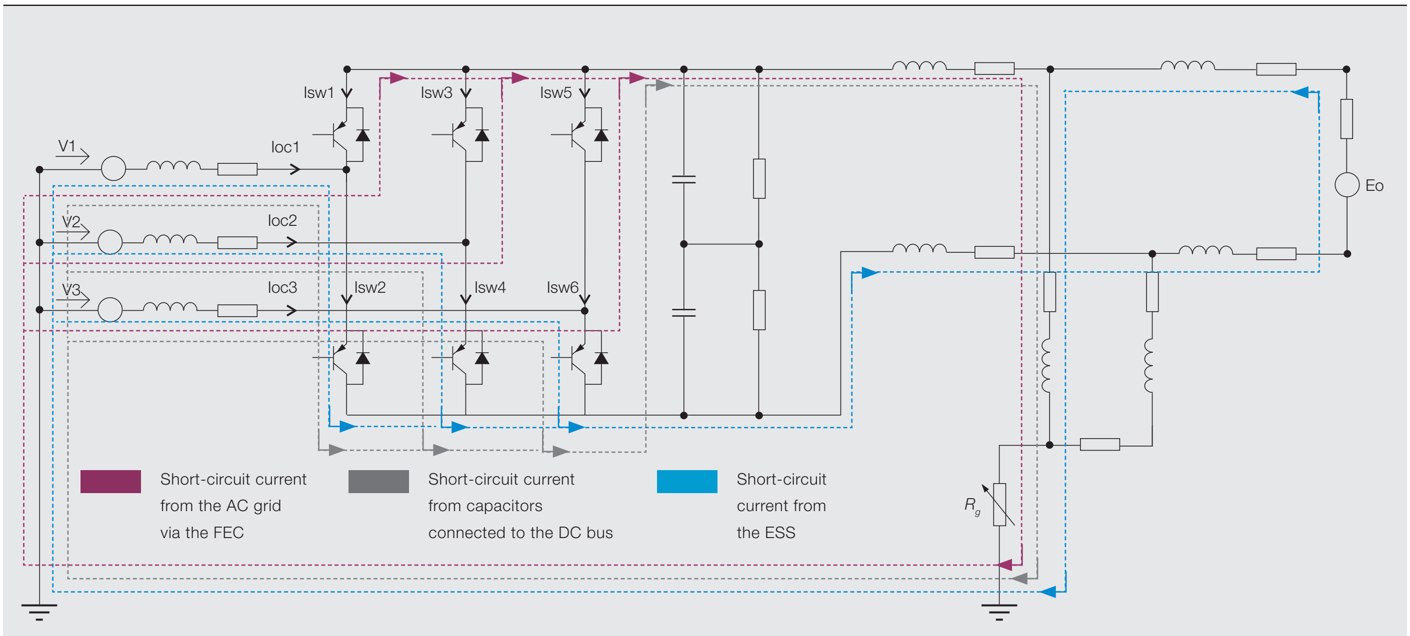
**Title picture**
When feeding renewable power from microgrids into a national grid, special measures have to be taken to protect the microgrid equipment from grid faults.

The most critical issue here is that when short circuits and ground faults occur on the DC side, most general-purpose converters are not able to limit fault currents. This happens in converters based on IGBTs with antiparallel freewheeling diodes – the most common design → 1. A large current from the AC grid may pass through the FEC's freewheeling diodes. Therefore, specific protection designs are needed. (It is worth noting that thyristor rectifiers cannot be used as front-end converters because when the power flow is reversed they require voltage polarity to be switched – with, obviously, serious implications for devices connected to the DC bus.)

If correctly sized circuit breakers are installed, even if the energy let through may lead to semiconductors overheating, current is limited, safety is preserved and further damage to the installation is prevented.

Thought has to be given to how to deal with fault conditions as PV plants and ESSs and their related electronics can behave in different ways during faults.

2 DC positive-pole ground fault current path with ESS and low fault resistance ($R_g$)




The two main types of faults that these designs have to protect against are DC short circuits and ground faults.

## DC side – short circuit

When a short circuit occurs between the terminals of a microgrid DC bus without any source on the DC side, different scenarios, which depend on the value of the fault resistance, may occur: for high values of fault resistance, the FEC may be able to maintain the DC voltage at the nominal value, but below a certain value, the FEC starts working in overmodulation mode.

The limit condition is when the short-circuit resistance is very small, approaching zero. At this point, because current flows in the freewheeling diodes, the FEC works as a rectifier in a short-circuit condition. In this case, current is no longer limited by the FEC. The short-circuit current is the sum of contributions from the AC grid through the FEC, from the capacitors connected to the DC bus and from the DC generators or ESS, if present → 1.

If a PV plant or an ESS is installed on the DC side, additional fault current is provided by the active generator – with each contribution depending on the microgrid structure. On the other hand, the active component, which includes a controller with its own voltage feedback loop, also helps keep the DC voltage at a value that is higher than in a passive DC grid. Therefore, the values of the short-circuit resistance for which the converter starts limiting the current absorbed from the AC side – and at which the control starts to operate in overmodulation conditions – are lower than in a passive DC network.

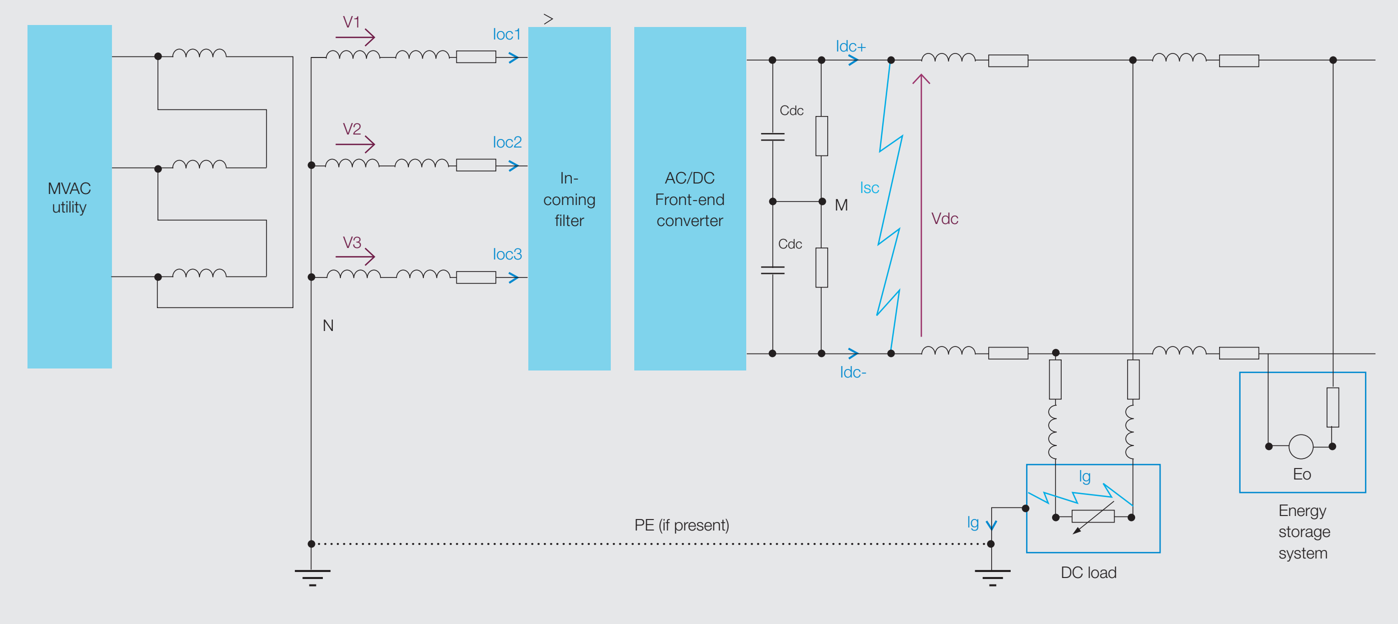
When short circuits and ground faults occur on the DC side, most general-purpose converters are not able to limit fault currents.

This means that, in systems equipped with a PV plant or ESS it is not possible to calculate the fault current by superposing the values that would be obtained from each single source, because each one affects the others in ways that are not immediately apparent. Fault currents should then be calculated in each case, taking the whole system into account.

## DC side – ground fault

DC sections of electrical installations are generally isolated from ground. On the other hand, for safety reasons, the transformer on the AC side of the FEC is typically grounded.

3 Microgrid scheme with transformer neutral point grounded for DC ground fault analysis




# The two main types of faults that designs have to protect against are DC short circuits and ground faults.

When a ground fault occurs on the DC side, fault currents may flow through the converter, with unexpected results.

In the case of a passive DC network, depending on fault resistance, scenarios similar to those described above also occur, with the converter moving into overmodulation mode and, finally, behaving as a rectifier. A PV generator, or an ESS, though contributing to keeping the DC voltage at a higher value than a comparable purely DC passive microgrid, provides a return path for a unidirectional current component at low values of the fault resistance.

In fact, a ground fault in one of the two poles of the DC grid generates a return path for the current toward the AC neutral point. For low values of fault resistance and if the fault occurs on the positive pole, the AC grid fault contribution passes through the freewheeling diodes of the FEC cathodic star, while the ESS contribution passes through the IGBTs of the FEC anodic star → 2.

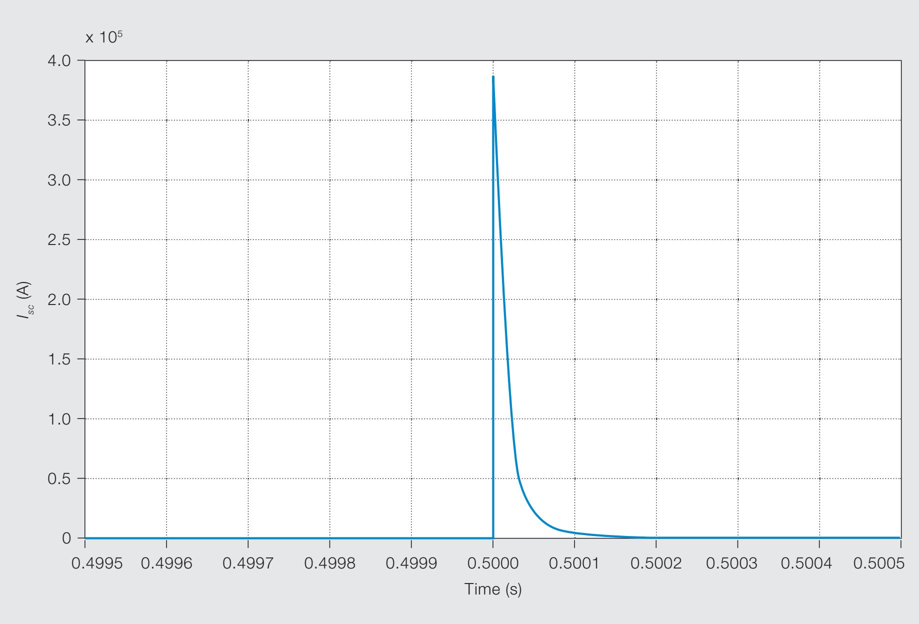
The situation is reversed if the fault occurs on the negative DC pole.

This can cause currents to flow out of both DC terminals of the FEC – instead of out of just one, which is the normal case. Such currents can be high enough to damage the FEC, yet it is a common mistake to neglect them when calculating ground fault current in the design phase.

In real applications, the electronic protection system embedded in the converter measures the voltage across the IGBT when its gate is pulsed. If this voltage is higher than a fixed threshold, the control circuit turns off the IGBT, pulling down the gate. This protection, called DESAT (desaturation) protection, blocks the IGBTs within a few microseconds of the current flowing through them, ex-

## In systems equipped with a PV plant or ESS, it is not possible to calculate the fault current by superposing the values that would be obtained from each single source, because each one affects the others in ways that are not immediately apparent.

4 Trend of fault current ($I_{sc}$) during a short circuit on the DC side




For the DC short-circuit case with a low fault resistance, fault current flows in the freewheeling diodes without any way for the IGBTs to limit it.

ceeding a set limit. Therefore, the fault current contribution of the PV plant, or of the ESS, is interrupted by turning off the modulation of the signal driving the FEC's IGBTs. Nevertheless, the AC grid fault contribution is still fed by the FEC through its uncontrolled freewheeling diodes. Therefore, a suitable external protection device must be installed to interrupt the fault current and protect the FEC.

## Case study

Several simulations were performed to analyze the behavior of the microgrid in → 3 during DC short-circuit and ground faults. Usually, the neutral point is connected directly to ground in order to avoid a dangerous voltage transfer to the low-voltage (LV) side in the case of a fault between the primary and secondary windings.

For the DC short-circuit case with a low fault resistance, fault current flows in the freewheeling diodes without any way for the IGBTs to limit it, even if an IGBT block signal is sent by the control system. The IGBT modulation turnoff is ineffective in this case because the diode connected in antiparallel to the IGBT makes the FEC work as a three-phase diode rectifier. The currents involved can reach values several times the FEC nominal current on the DC side (125 A, with $R_{sc}$ = 1 m$\Omega$) → 4.

With low fault resistances, the FEC contribution to the short-circuit current may reach values up to 16 times that of the FEC nominal current on the DC side.

For the DC ground fault case with a low fault resistance, fault current flows in the freewheeling diodes of the cathodic star, without any way for the IGBTs to limit it, as well as in the IGBTs of the anodic star. The currents reach values several times that of the FEC nominal current on the DC side (125 A, $R_g$ = 100 m$\Omega$) [1]. The IGBT modulation turnoff can interrupt the ESS contribution only.

Depending on the value of $R_g$, the current on the AC side may be completely positive and all of the AC component that is absorbed by the converter during a fault transfers power to the fault [1] → 5.

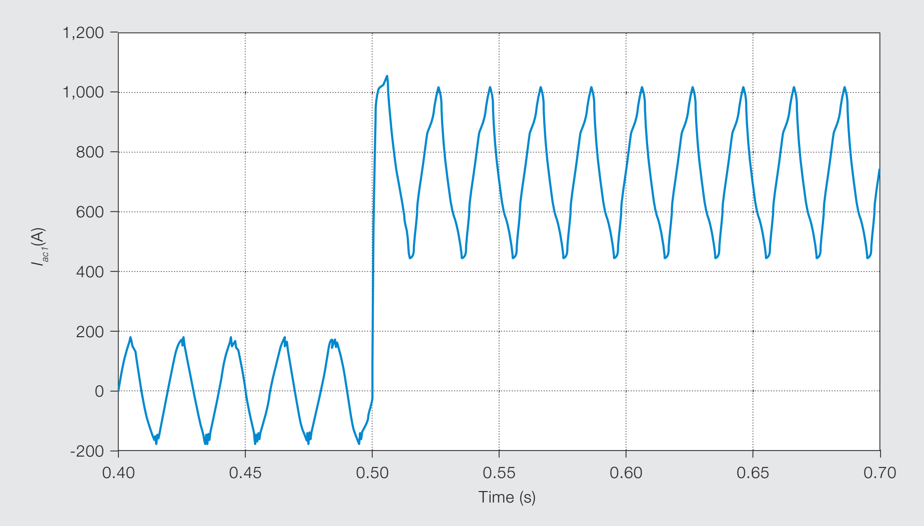
With the decrease of $R_g$, the FEC contribution to the short-circuit current may reach values up to 27 times that of the FEC nominal current on the DC side. Such a contribution cannot be removed by the IGBT block since it passes through the freewheeling diodes.

## Fault protection analysis

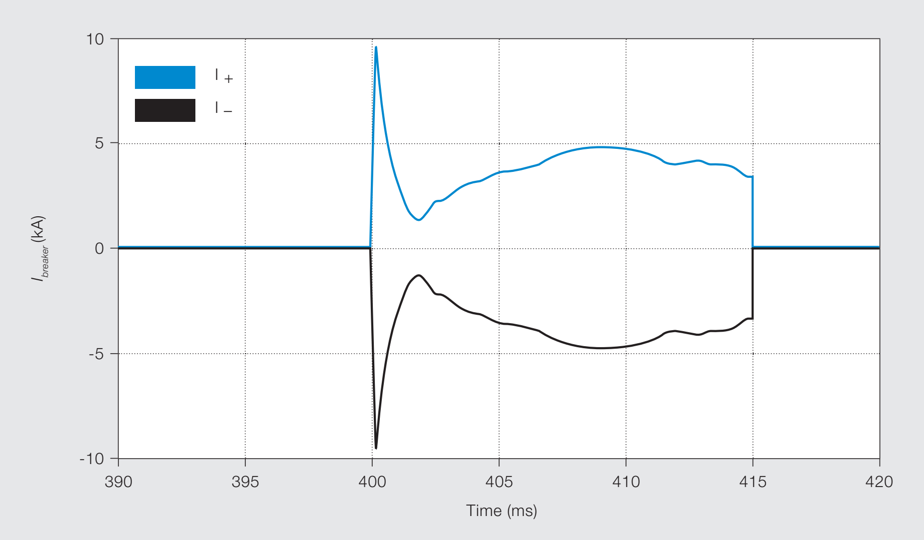
It is worth noting that while for DC short-circuit protection a unipolar breaker could be used, but for a ground fault a bipolar circuit breaker is necessary since the PV system and the ESS can supply the fault through the healthy DC pole and, moreover, the ground fault is equally likely to occur on either the positive or negative DC pole.

With increasing interconnections of LVDC micro-grids and AC power grids, sophisticated fault protection will become an essential part of power system design.

5 Trend of $I_{ac1}$ current during a ground fault on DC side with ESS and $R_g$ = 100 mΩ




6 Currents flowing in the two poles of the circuit breaker




## DC short-circuit analysis

For the DC short-circuit simulation, the modulation is turned off after a typical DESAT protection time (2 µs), while tripping is delayed 15 ms to simulate a DC circuit breaker → 6 [2].

To reduce overvoltage, the circuit breaker is located downstream with respect to the DC bus capacitances. Because of the DESAT protection, the currents depicted in → 7 flow in the FEC diodes.

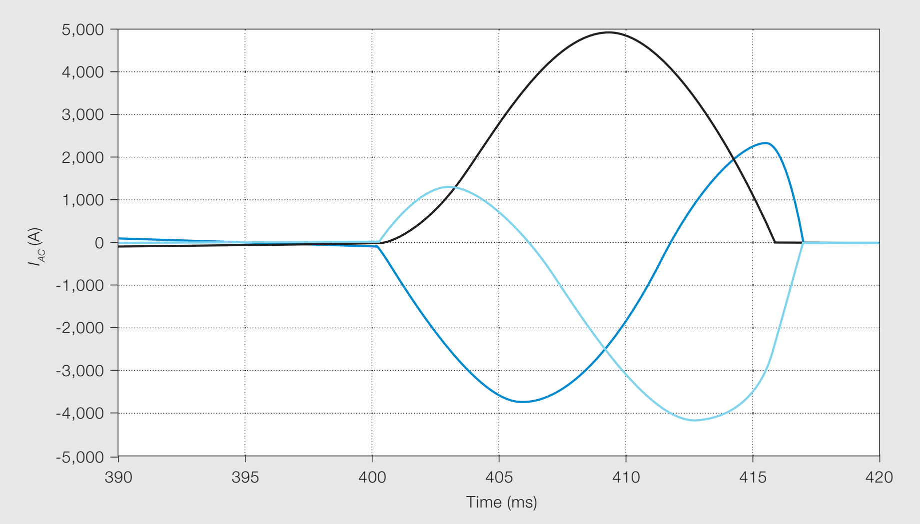
The energy content of a transient (the $I^2t$) during interruption is about 170 kA²s. This value is too high for the FEC used. For the semiconductors considered in the simulation, the allowable $I^2t$ value is 42 kA²s. Therefore, some oversizing of diodes is required to make the FEC capable of withstanding the transient.

## Ground fault analysis

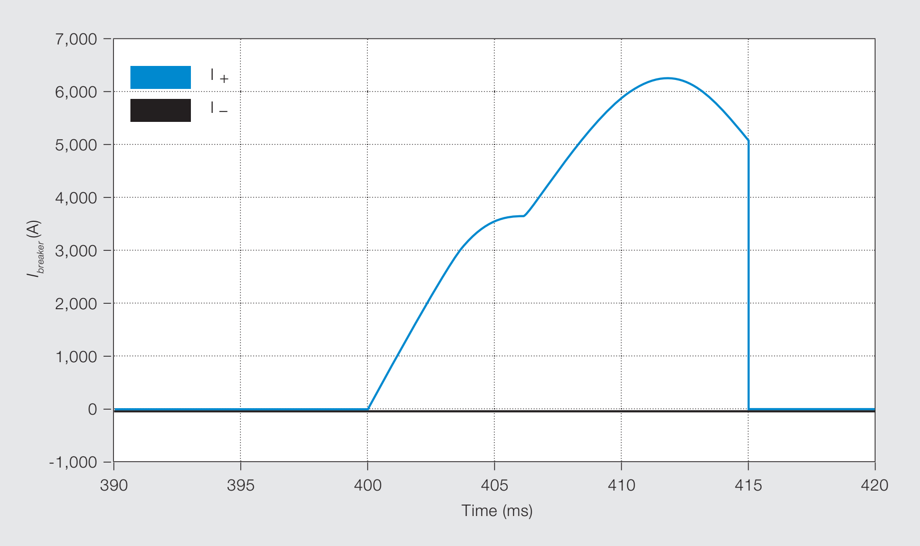
The same fault as described above was simulated between the positive DC pole and ground, with interruption by a DC circuit breaker [2]. Resulting AC currents were similar to those of the pole-to-pole short circuit. On the other hand, currents flowing through the DC poles of the FEC are very different → 8. Indeed, the current through the faulty pole increases while the other remains close to zero, thanks to the DESAT protection. The $I^2t$ is about 157 kA²s and is comparable with that of the short circuit. Oversizing of diodes is again required.

In summary, DC pole-to-pole and pole-to-ground faults in DC grids fed by an FEC and equipped with PV generation systems and/or ESSs cannot be neglected. Further, DESAT protection is not enough to protect the FEC switching

7 AC currents in the three phases during the circuit breaker trip




8 Currents flowing in the two poles of the circuit breaker




components as turning off the IGBT modulation does not limit the currents flowing through the freewheeling diodes. For this reason, specific protection devices have to be introduced and carefully dimensioned in order to safely interrupt fault currents and limit consequential damages.

With increasing interconnections of LVDC microgrids and AC power grids, sophisticated fault protection will become an essential part of power system design.


**Marco Carminati**

**Enrico Ragaini**

ABB Electrification Products,

Protection and Connection

Bergamo, Italy

marco.carminati@it.abb.com

enrico.ragaini@it.abb.com


**References**


[1] M. Carminati *et al.*, “DC and AC ground fault analysis in LVDC microgrids with energy storage systems,” in *Proceedings of the IEEE 15th International Conference on Environment and Electrical Engineering,* Rome, 2015, pp. 1047–1054.

[2] M. Carminati *et al.*, “Fault protection analysis in low-voltage DC microgrids with PV generators,” in *Proceedings of the 5th International Conference on Clean Electrical Power Renewable Energy Resources Impact,* Taormina, 2015, pp. 190–197.