Introduction

The amount of installed distributed energy resources (DERs) has significantly increased in Germany. Within the last 10 years, the renewable's installed power has risen by more than 69 GW up to 93 GW in the year 2015. Around 42% is related to solar power with a share of 60% being connected to the low-voltage grids [1]. The connection to the grid is established using inverters.

The infeed of inverter interfaced distributed generator (IIDG) changes the classical power flow within the grids. While voltage band violations and overloading pose challenges for the grid in the normal operation mode, the situation during grid faults can also be affected. IIDG contribute to the fault currents depending on the fault, grid topology and facilities, their type and control, the volatile availability of primary power, as well as the positioning within the grid. Current and voltage at the position of grid's protection systems are thereby affected, which can have an impact on the functionality of the line protection regarding the tripping times up to a non-functioning (Fig. 1). This effect is called blinding of protection. In previous works of the authors, it was already shown that IIDG can lead to blinding especially of NH fuses in artificial low-voltage grids [2].

The following investigations concentrate on IIDG in low voltage (LV) grids. The impact of different IIDG distributions is shown with parameter studies using a steady-state short-circuit calculation method capable of regarding IIDG fault current. The results show the impact of different infeed configurations on the short-circuit currents in the CIGRE LV benchmark grid, considering different fault positions and types. The IIDGs are configured to follow the present and future VDE-AR-N 4105 guideline. The IIDG LV benchmark grid does not cover all worst-case scenarios for the analysis of blinding of protection in German grids. It is shown that the usage of digital (directional) overcurrent detection can be a proper solution to cope with the lower short-circuit currents. The combination of a fuse link allowing the triggered disconnection in the overcurrent range can be a promising solution, especially regarding the retrofit of existing feeders. Laboratory tests with a prototype show a reliable tripping with tripping times of <300 ms.

1 German low-voltage regulations

The behaviour of different DER types in German low-voltage grids in case of grid faults is regulated in the VDE-AR-N 4105 guideline [4]. Presently, a draft for a new revision is released to replace the guideline from 2011 [5]. Amongst others, changes regarding the behaviour in case of voltage drops due to grid faults are proposed. In the following, the focus is on the behaviour of Type 2 DERs such as IIDG.

In version 2011, a distinction of the undervoltage switch off criteria is made depending on the IIDG's power at the point of common coupling (PCC). In case of a total IIDG power below 30 kVA, the drop of one of the line-to-ground voltages \( V_{LE} \) below a value of 0.8 \( V_N \) is decisive for a disconnection of the IIDG within 200 ms. For IIDG with a power exceeding 30 kVA additionally a drop of one of the line-to-line voltage \( V_{LL} \) below a value of 0.8 \( V_N \) requests a disconnection of the IIDG.

The new revision of the guideline claims IIDG to reduce the infeed current to <10% of the nominal phase current within 60 ms once any \( V_{LE} \) drops more than 0.8 \( V_N \). At the same time, IIDG is required to stay synchronised with the grid for a certain time, depending on the smallest \( V_{LE} \) at the PCC (Fig. 2). This behaviour is called fault ride through or low-voltage ride through.
impedance of $3.2 + j12.8\, \text{m}\Omega$. The external grid's short-circuit power is 100 MVA with an $R/X$ ratio equal to one.

In alternation to the given CIGRE configuration [6], three-phase IIDG models are considered for the DER. The behaviour of the IIDG is modelled to follow an asymmetric fault current infeed (1) with an asymmetric active power-maximisation to 1 pu as long as the maximum phase current is not exceeded.

$$I_{\text{IIDG}} \propto f(V_{L1})$$

$$I_{\text{IIDG}} \propto f(V_{L2})$$

$$I_{\text{IIDG}} \propto f(V_{L3})$$

(1)

The maximum phase current is limited to 1.3 times of the nominal current (2). An active current infeed with $\cos(\varphi) = 1$ is considered.

Regarding the undervoltage limits the three scenarios described previously are taken into account (Table 2).

A short-circuit-current calculation parameter study is used to analyse the effect of the IIDG on the fault current seen by a potential protection device at the beginning of line 1. To perform the calculations, a tool for stationary short-circuit-current calculations based on a current-source superposition method is used [7]. The tool is able to consider the current-source behaviour of the IIDG. The fault scenarios shown in Table 3 are calculated in all permutations.

A 250 A NH2 fuse is assumed as feeder protection element for all calculations. The minimum fault current and the resulting tripping time of the NH fuse are used for the comparison of the individual calculations. The tripping time is evaluated according to the time–current characteristic of an NH2 fuse. Fusing currents below the fusing current of $1.6 \cdot I_{\text{N}}$ will lead to an uncertain or no-tripping and are depicted as blinding cases as follows [8].

Only those calculation results are evaluated in which a mathematical convergence is met. Furthermore, only those fault situations are regarded, which would be cleared reliably by the assumed fuse $I_{\text{fusive}} > 1.6 I_{\text{N}} = 400\, \text{A}$ in the passive grid without IIDG infeed.

At first, the original scenario of the CIGRE benchmark grid is investigated. The original IIDG power distribution with a total power of 72 kW is taken into account (Fig. 3). To additionally cover different pre-fault situations, the infeed power is evenly adjusted to 30, 70 and 120% of the original power.

The results show that the minimum current at the feeder protection remains above 400 A for the old and new VDE-AR-N 4105 guidelines [9].

The results show that the minimum current at the feeder protection remains above 400 A for the old and new VDE-AR-N 4105 guidelines for all power variations (Fig. 4). Therefore, a proper functionality for all fault cases can be expected also under the influence of these IIDGs.

To investigate the impact of a further increased infeed scenario, the infeed currents of the IIDGs are changed in a second step, while the grid topology as well as the IIDG's PCCs remain the same. The five IIDG maximum currents are permuted in six steps (3). Only those IIDG permutations are regarded that meet the requirements in (4) in order to ensure the maximum infeed to remain below the nominal fuse current. At the same time, only Configurations with a total power above the previous scenario are taken into account

$$I_{N,M,X} \in \begin{bmatrix} 0\, \text{A}, & 50\, \text{A}, & 100\, \text{A}, & 150\, \text{A}, & 200\, \text{A}, & 250\, \text{A} \end{bmatrix}, \forall\text{IIDG}, X$$

(3)

$$\sum_{X=1}^{m} I_{N,M,X} \leq 250\, \text{A}, \forall m \text{ variations}$$

(4)

A load flow calculation is carried out for all permutations to investigate the requirements for the voltage limits $[\text{max}(V_{L1,L2,L3} < 1.1\, \text{pu})]$ in a normal state with full infeed while

Table 1 Line parameters CIGRE LV benchmark grid

| Line | Length, m | Type | Size, mm$^2$ |
|------|-----------|------|-------------|
| 1–9 (main feeder) | 35 | NA2XY | 240 |
| 10–17 (side feeders) | 30/35 | NA2XY | 50 |

Table 2 LV guideline AR-N4105 low-voltage restrictions

| AR-N 4105-11 | AR-N 4105-2017 (draft) |
|----------------|-------------------------|
| $P_{IE} < 30\, \text{kVA}$ | $P_{IE} < 30\, \text{kVA}$ |
| $V_{LE} < 0.8\, V_{N}$ | all power levels |
| $V_{LE} < 0.8\, V_{N}$ | with connection criteria |
| $V_{LE} < 0.85\, V_{N}$ | and remaining according to characteristic curve |

Table 3 Fault scenarios for parameter study

| Parameter | Values |
|-----------|--------|
| fault node | (2)...(18) |
| fault type | 3ph(−e), 2ph(−e), 1ph−e |
| fault impedance | 0/1/2/4/6/10/21.5/46.4/100/215.4 mΩ |

Fig. 4 Minimum fault current for original CIGRE IIDG configuration
As mentioned before, the current draft of the VDE-AR-N 4105 guideline defines a threshold value of $0.85 \cdot V_N$ for a constant infeed once a line-to-ground voltage drop of more than $0.8 \cdot V_N$ occurs in one of the phases. With a redefined undervoltage threshold of $0.85 \cdot V_N$ the minimum fault currents are increased by up to 250 A for a number of fault cases in contrast to the results with a threshold of $0.8 \cdot V_N$ (Fig. 9). In these cases, one or more additional IIDGs are disconnected due to the PCC voltage criterion. This reduces the effect of blinding for these fault cases. Still the overall minimum fault currents for the individual IIDG configurations do not change severely due to the changed voltage threshold.

Nevertheless, almost all minimum fault currents remain above 275 A for the investigated IIDG configurations (Fig. 10). For these cases, a detection using a digital overcurrent mechanism, parameterised to a pickup current of 1.1 \cdot 250 = 275 \text{ A} could be used to sense the fault, while still allowing load and infeed currents of 250 A. The remaining six IIDG configurations show minimum fault currents below the nominal fuse current of 250 A. To maintain a full infeed capability of 250 A, a directional overcurrent detection method with a threshold of 230 A; 190 A for the last IIDG configuration in load current direction would be a suitable solution, since the fault currents are in load direction for all cases. Since conventional NH fuses cannot be used in combination with a digital trigger, a switching element is needed along with the detection mechanisms. Different solutions such as circuit breakers are possible, but mostly quite costly, especially when retrofitting an existing, fuselink-based substation [9]. An enhanced NH fuselink with the capabilities to be triggered by an external low-power signal can be a suitable alternative [8]. This allows maintaining the excellent capabilities of the fuselink in terms of switching of high fault currents along with the intrinsic current limiting functionality of the fuselink. At the same time, it would allow the triggered ‘disconnection’ of the fuse in the ‘overcurrent range’, close to the nominal current with the help of a digital trigger signal.

These types of fuses with a traditional functionality in the high-current range, combined with an external trigger for the low-current area, are already known for special DC applications, especially in the automotive sector [10]. One possible realisation is based on the combination of the fuselink with an additional grounding switch (contactor) to increase the fault current through the fuse. With the use of this contactor in combination with a digital protection relay, an additional interconnection to ground potential at one fuse pole is achieved. Consequently, a high short-circuit current flows through the fuselink, resulting in a reliable and fast disconnection of the fuse.

When applying this concept to the previous simulation results (Fig. 10) with a directional current pickup limit of 190 A, a reduction of all tripping times can be achieved (Fig. 11).

To keep the requirements for the additional digital detection mechanism, and therefore the technical complexity and cost low, a delay of the digital detection part of 1 s is assumed. All faults leading to tripping times below this value will be cleared by the conventional fuse functionality. The system also allows a
dependent maximum current time relay characteristic to allow selectivity with subsequent fuses.

4 Laboratory analysis of triggered fuses

To test the approach of a triggered fuse along with a digital overcurrent detection, a 100 A NH2 fuse prototype was constructed by ETI [10]. The prototype was then tested in the IFHT laboratory using the setup shown below (Fig. 12).

The setup consists of an LV main feeder (762 m NAYY 150 mm²), supplied by 10/0.4 kV 250 kVA transformer. Conventional three-phase PV inverters with a total power of 75 kW are connected at two side feeders (NAYY 35 mm²). The PV inverters are parameterised according to the VDE-AR-N 4105-11 guideline. As classical protection, a conventional 100 A NH2 fuse is used as a reference as well as a 100 A NH2 prototype of a triggered fuse. An ABB Ref630 overcurrent-protection relay provides the trigger signal. A small contactor relay closes the connection to ground in case of a trigger signal by the relay. With the help of an LV short-circuit emulator, a single line-to-ground fault with different impedances is replicated.

Due to the fact that the NAYY 150 mm² cables available at the IFHT laboratory have a nominal current of 275 A (underground), the used 100 A NH2 fuse as line protection is very small. To test the blinding effect, therefore, fairly high fault impedances (Table 5) had to be considered in order to show the principle functionality. Tests with a more suitable 250 A NH2 prototypes are planned and will follow shortly.

Six individual tests were carried out, considering two different fault impedances. First, a conventional NH2 fuse was tested without and with the infeed of the inverter. Afterwards, the trigger fuse was tested in two steps. For 25 min, the infeed current of the inverter was carried by the fuse before the fault was initiated. For test 3, the digital overcurrent relay was configured to act non-directional with a tripping current of $I_{N_{fuse}} = 130$ A and a delay of 500 ms. For test 6, the relay was reconfigured with a directional functionality and a forward tripping current of $0.8 I_{N_{fuse}} = 80$ A, while the backward direction remained at 130 A.

Test 1 shows an root-mean-square (RMS) current of 230 A across the fuse, resulting in a fusing time of the conventional fuse of 4.6 min. Owing to the infeed of the IIDG, the current carried by the fuse is reduced to 135 A, is smaller than its conventional fusing current of $1.6 I_{N_{fuse}} = 160$ A. As expected, the NH fuse does not trip within the 25 min test time. As expected, the triggered fuse does not operate within the first 25 min with IIDG infeed and no grid fault in test 3. After fault initiation, the digital relay detects the fault within 20 ms, followed by the parameterised 500 ms delayed tripping signal. After tripping signal initiation, the auxiliary contactor takes 63 ms to close, followed by 127 ms of fusing time. The overall tripping time is, therefore, 710 ms, while the 500 ms tripping time of the protection relay can be reduced.

In test 4–6, the fault current is reduced further. Test 4 shows an RMS current of 190 A without IIDG, resulting in a fault current of 90 A with IIDG infeed in test 5. As expected both do not lead to a
fusing of the conventional fuse, as the fault current with IIDG is 10% below the nominal fuse current. In the next test 6, the directional overcurrent relay parameterisation is used for detection purposes. The IIDG infeed current is 100 A for the first 25 min under normal grid operation and does not lead to any tripping of the protection system, as intended. After initiation of the fault, the current direction in the faulty phase changes and settles to 90 A similar to test 4. This is also detected by the relay within 20 ms followed by 500 ms of parameterised delay for closing the auxiliary contactor. The contactor itself has again a delay of 63 ms, and the additional fusing time is 125 ms. Therefore, even a slightly lower overall tripping time of 708 ms is achieved.

The experimental results from the laboratory show that the proposed system works as expected for low-current fault situations. Even faults with a current below the nominal fuse current can be handled properly. No significant difference in overall tripping times in dependency of the fault current can be determined. Still, it has to ensure that the parameterisation of the digital protection detection mechanism does not lead to overreactions due to the load current. Prior investigations showed that the fault current is in ‘load current’ direction, meaning that the directional parameterisation of overcurrent protection can pose a suitable option for infeed-dominated grids in low voltage.

5 Conclusion and further work

The simulative investigations show that the infeed of IIDG considering the original CIGRE LV benchmark grid along with the given inverter power levels would not lead to blinding of a 250 A NH fuse as feeder protection. When considering different, especially higher IIDG power distributions, the simulated tripping times increase up to a blending of the fuse. Adjusting the benchmark configuration to a more suitable worst-case configuration for German grids shows that the phenomenon of blinding occurs for several infeed configurations. It is discussed if the problem can be solved with the help of different digital overcurrent detection mechanisms. The combination with triggerable fuses, which allow a triggered blowing of the fuse for overcurrents, is presented as a promising solution, especially for retrofit applications. Prototypes of the fuses were successfully tested in the IFHT testing centre showing a reliable tripping within <1 s. Further development, especially of functional, reliable and cost-efficient digital detection relays is necessary.

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7 References

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