Future standardisation requirements for dependable overcurrent protection in intentionally islanded LV microgrids build by distributed inverters

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Abstract: The preconditions for dependable overcurrent protection of customer installations are largely unknown in islanded low-voltage (LV) microgrids build by multiple droop controlled and current limited inverters. Consequences may be an islanded operation with limited reliability of supply, investments of uncertain necessity or uncontrolled hazards. Distribution system operators will not opt for intentional islanding until those risks become predictable. Extensive variation studies are therefore performed to screen for decisive influencing factors and to quantify their effect by means of computer simulations in Matlab/ Simulink®. First steps of a standardisation roadmap are drawn that will either enable developing the preconditions for a dependable overcurrent protection or choosing effective alternatives. An initial set of quantitative minimal conditions is given as a basis for further discussions.

1 Introduction

A low-voltage (LV) microgrid can be intentionally islanded for backup power supply when a sufficient capacity of distributed generators (DGs) is installed and coordinated adequately [1]. Conventional overcurrent protection may no longer operate dependably as available short-circuit currents will typically be smaller than in grid parallel operation (GPO) [2]. Especially inverter interfaced DG (IIDG) will contribute a limited current level. The distribution system operator (DSO) needs to design an appropriate strategy for protection of the backup island (Table 1).

Overcurrent protection is widely assumed to be infeasible for feeder protection in islanded mode of operation (IMO) when using devices (e.g. fuses) with ratings identical to GPO. Protection of radial feeders can be accomplished by relays utilising voltage criteria with directional time grading [2, 3].

Opposing opinions exist on the usability of conventional overcurrent protection in customer installations during IMO [2–5]. The overcurrent protection devices (OCPDs) for GPO can be used without alteration, when a dominant unit of sufficient rating is responsible for supplying a fault current to the main LV busbar. In a multi-source island fault currents are fed from distributed locations, superposing to the total fault current. Hints exist that an unfavourable partial extinction of fed in limited IIDG currents may occur reducing the available fault current even further [2, 6]. The relevant mechanisms may be related to circular currents in normal operation or to a loss of transient stability, when droop control is employed for the source coordination. The effects have not been quantified and therefore their relevance cannot be assessed. Furthermore, the key influencing factors remain unknown.

This paper points out selected results and conclusions from research performed on the precondition of dependable overcurrent protection in customer installations of intentionally islanded LV microgrids build by multiple IIDG [7]. These investigations can be seen as first steps on a roadmap of identifying decisive factors, pointing out measures to develop and standards to define.

2 Modelling and methodology

2.1 Microgrid structure

Fig. 1 shows the microgrid structure assumed. A three-phase four-wire AC distribution system with neutral conductor is chosen for this study. Its feeders are operated radially. For further component data refer to [7]. The transformer feeding in GPO remains outside the microgrid in IMO. The disconnection happens by a regular switch, assuming a blackstart of the island for backup power supply.

No dedicated sources or components are used for star point treatment or fault current supply. Instead, the IIDGs are assumed to consist of a mixture of such with (IIDG4) and without (IIDG3) controlled neutral current injection capability. The IIDGs do utilise LCL filters but not transformers (e.g. Yd switching group). Star point treatment and fault current supply therefore rely on the IIDG solely.
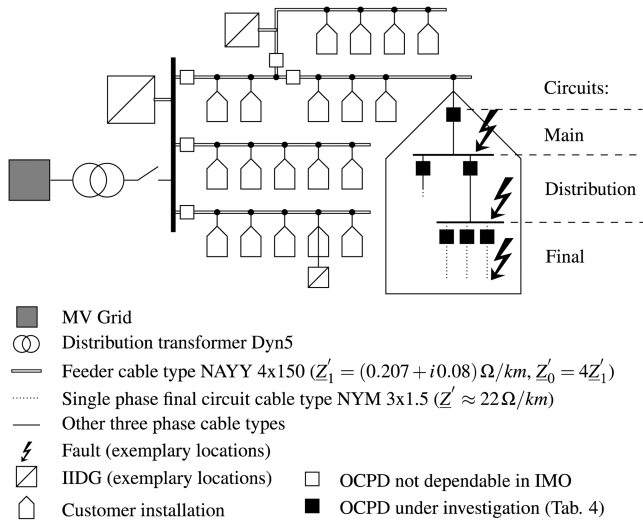
All IIDGs participate in grid building. Their coordination happens by a $f(P)$–$U(Q)$ droop control. An islanding scenario with two active IIDGs is investigated. The IIDGs are connected to the island at arbitrary places, restricted by current carrying capacities and voltage rise limits in GPO. Interconnection lines are taken into account. Faults are considered in customer installations outside the IIDG locations (Fig. 1). Cable types and lengths used reflect German typicals and standards. Single-phase final circuits are of type NYM 3×1.5 with a maximum length of 20 m. A no-load scenario is investigated. On the one hand, this is a special case from the operational point of view. On the other hand, a high degree of influence by current limiting mechanism (CLM) design in asymmetrical fault cases is expected. A reduced impedance topology may then be used as given in Fig. 2. A sophisticated variation of those line impedances can cover almost any realistic relative and absolute position of IIDG and faults in a microgrid as given in Fig. 1 [7].

2.2 Inverter control and limitations

The IIDGs behave as grid supporting units with voltage source behaviour [8]. The control is performed by a cascaded multiloop control (droop, voltage and current control) in the stationary reference frame $\alpha\beta(0)$ resembling [9]. Voltage feed-forward and virtual impedances are used (Fig. 3). Zero sequence controllers are

Table 1 Exemplary protection strategies for backup islands

	Shutdown[1]	Selective fault clearing[2]
Pros	cost-saving	scalable selectivity
		high degree of robustness
		DSO 'in control'
Cons	difficult fault location	expensive
	limited robustness of island (e.g. blackout for final circuit fault)	
	unknown dependability of shutdown of all sources	

[1]shutdown of backup island on faults (second contingency)
[2]continuous operation when and where possible

Fig. 1 General microgrid structure with OCPD locations

Fig. 2 Reduced microgrid model. Legend: refer to Fig. 1

added for IIDG with neutral conductor current injection capability (IIDG4) [7]. Harmonic control is neglected.
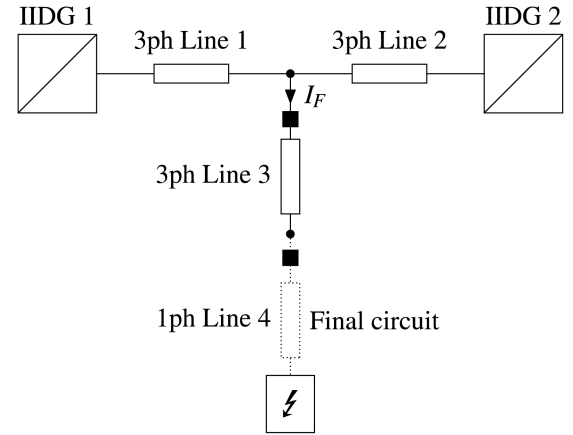
The rated maximum IIDG current of phase and neutral conductors I_r is assumed as 1.1 p.u. of the nominal current. This reflects a worst case for overcurrent protection.

Current limitation is done by limiting the reference current output of the voltage controllers (Fig. 3). The CLM investigated resemble [10] in that amplitude and phase estimators are used to dynamically calculate scaling factors. The latter are applied to the original current references. Supplementary time-domain saturation approaches are used to increase transient performance. Additional variants of CLM to those given in literature are developed for IIDG3. New CLM approaches are systematically created for IIDG4 that account for neutral conductor current limitation for the first time (see [7]). All 52 CLM variants implemented are tested by simulations. Voltage sags are applied to an IIDG with varying sag depths and types. The latter include the default types A-G [11] and four newly identified ones occurring in inverter-based islands [7]. Criteria are defined and applied in a worst-case manner to assess the CLM performance. Only four suitable CLMs remain per IIDG category (IIDG3 and IIDG4), which can be explained by the identified design rules [7]. Those CLMs are investigated in homogeneous and diverse combinations between the IIDG.

A static proportional anti-windup (AWU) controller is employed to compensate for transient and steady-state error signals of the voltage controller due to an activated current limitation (Fig. 3). The concept is known from [12] and is applied here in the stationary reference frame including the zero sequence. Hierarchical AWU concepts including the droop controller are not considered here. Instead, their potential use is investigated prior to a further development in case of asymmetrical faults [6].

Voltage limitations of all kinds are neglected in this study to determine the influence of current limitation and star point treatment by the IIDG on the required voltages and to assess the feasibility. DC-side voltage deviations are not considered.

Power limitations are also neglected. A four-quadrant operation of all IIDG is assumed. Reduced primary power availability prior

to a fault is taken into consideration, but primary side dynamics and stability issues are out of scope.

2.3 Simulation model and assumptions

The simulation models are formulated in the time domain to account for individual frequency references per IIDG. The models represent AC signals directly in the time domain (e.g. voltages, currents). A discrete solver is used with a fixed step width of 50 μs.

Inverters are represented by average value models [13]. A worst-case investigation is performed hereby, as higher frequency switching phenomena will likely decrease over-current tripping times [14]. The same is valid for the neglected harmonic control. The primary side of the IIDG is modelled as an ideal DC voltage source. This neglects primary side dynamics, steady-state behaviour and limitations, but allows for an a-posteriori check of technology-specific restrictions.

The sequence of events remains identical per simulation run. A blackstart is performed as at $t = 0$ s without loads by ramping up the IIDG voltage references. The simulated system may settle until $t = 2$ s ($t_F = 0$ s) when a fault is introduced. The system's fault behaviour is simulated until $t = 5$ s ($t_F = 3$ s). Those time spans are in the range or exceed five times the droop delay constants chosen and allow for at least qualitative prediction in case of longer fault durations.

2.4 Design of experiments (DoE)

Fault types investigated are three-phase and single-phase faults (phase-neutral). The former ones are restricted to three-phase sections of customer installations. Single-phase faults are investigated in islanding scenarios (IScs) with increasing diversity of inter-IIDG CLM and structure (Table 2). Variations of IIDG substructures and parameters are performed in up to 32 dimensions per ISc. A radial Morris screening approach is used [15] that enables a parameter space filling DoE. Intra-IIDG dependencies and design restrictions as well as microgrid design requirements are taken care of [7]. Exemplary aspects of variation are given in Table 3. An adaptive parameterisation is developed for the IIDG controllers [7]. The number of simulation runs is given in Table 2.
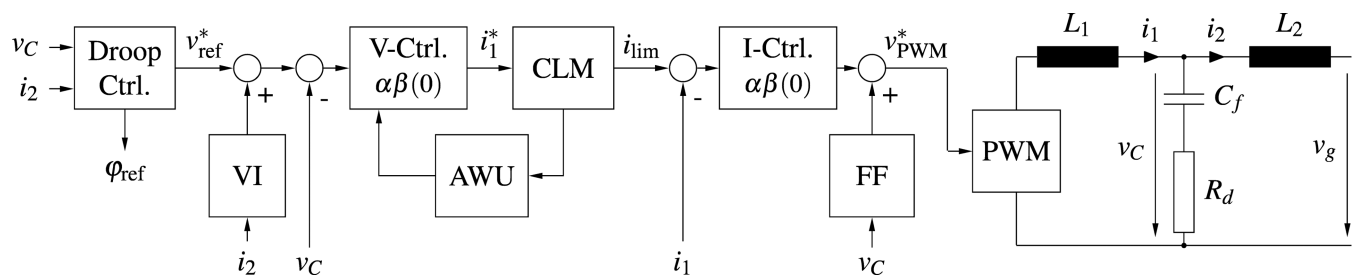
Fig. 3 *Simplified IIDG model in single-phase representation. AWU: anti-windup compensator, PWM: average value model of inverter (Section 2.3)*

Table 2 Definition of IScs investigated

Islanding scenario	IIDG type combination	CLM combination	Fault type	Simulation runs
ISc1	4 + 4	homogenous	1ph	4960
ISc2	4 + 4	diversified	1ph	3600
ISc3	3 + 4	diversified	1ph	3600
ISc0	all	both	3ph	6800

Table 3 Subset of variations performed within Isc1 to Isc3

Factor	IIDG	Range	Unit	Base
Grid + fault				
relative position of IIDG fault	—	1–5	—	—
distance of IIDG	—	0.01–1.2	km	feeder
distances of IIDG fault	—	0.01–1.2	km	feeder
final circuits (single-ph.)	—	0–20	m	—
fault inception angle	—	−90° to 90°	—	voltage
IIDG ratings				
apparent power S_r	1	10–100	kVA	—
	2	0.3–3	p.u.	IIDG 1
LCL grid side inductor	1	0.03–0.1	p.u.	$Z_{B,1}$
	2	0.3–3	p.u.	IIDG 1
LCL capacitor	1	0.01–0.15	p.u.	$C_{B,1}$
	2	0.1–5	p.u.	IIDG 1
Droop				
power calculation type	1, 2	1–2	—	—
delay time constant	2	0.5–2	p.u.	400 ms
prefault active power	1	0.3–1	p.u.	$S_{r,1}$
	2	0.3–1	p.u.	$S_{r,2}$
Virtual impedance				
impedance	1, 2	0–0.1	p.u.	Z_B
impedance angle (inductive)	1, 2	0°–90°	—	—
Voltage control				
scaling of gain/speed	1, 2	0.9–1	—	—
Current control				
scaling of gain/speed	1, 2	0.9–1	—	—
Current limitation				
CLM combination	—	1–4/6/16	—	ISc1/2/3
Anti-windup				
AWU gain	1, 2	0.5–1	—	—

3 Exemplary results

To enable tripping of OCPDs in customer installations within the required tripping times, a minimal tripping current $I_{a,min}$ has to be supplied at the OCPD location (Table 4). The focus of this paper lies on the investigated impacts on fault current in case of one-phased faults. For further aspects investigated (voltages, powers, three-phased faults) refer to [7].

3.1 Initial fault current supply by IIDG

Theoretically, the IIDG could drive a fault current at the OCPD location equal to the cumulated rated maximum IIDG currents as determined by their current limi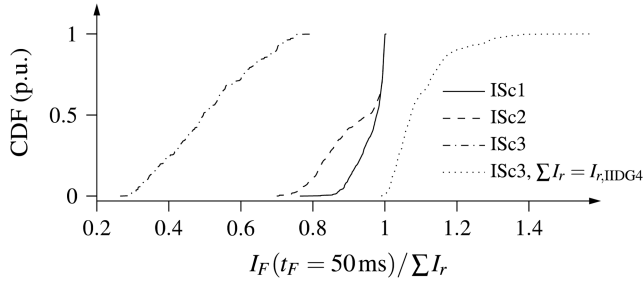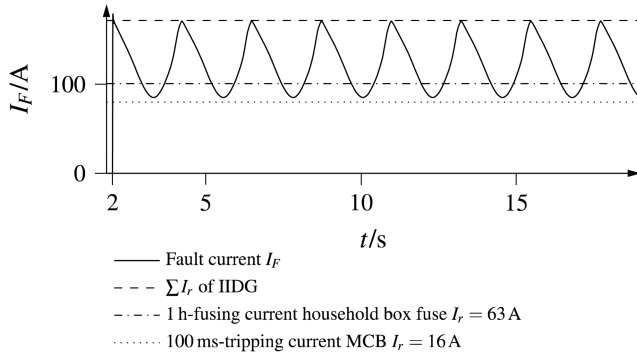tation. Fig. 4 shows the empirical cumulated density function (CDF) of the initial fault currents 50 ms after fault inception relative to the cumulated rated maximum currents.

An influence on the CDF minima and spread exists by the degree of diversity of inverter control structure and current limitation. Inside scenarios with IIDG4 only (ISc1, ISc2), the major influence on the CDF is the type and combination of current limitation approaches used (see [7]). In case of mix of IIDG3 and IIDG4 (ISc3), the rating of the IIDG4 dominantly influences the available initial fault current (see [7]). It is equal to or exceeds the maximum rated current of the IIDG4 (Fig. 4).

Table 4 Tripping data of OCPD investigated exemplarily in the circuits from Fig. 1

Circuit	Type	Characteristic	Standard	I_n, A	t_{req}, s	$I_{a,min}/I_n$, p.u.	$I_{a,min}$, A
final	MCB	B	[17]	16	0.4	5.0	80
	fuse	gG	[18]	16	0.4	6.9	110
distribution	fuse	gG	[18]	35	5	4.0	140
main	fuse	gG	[19]	50	3600	1.6	80
				≥63	7200	1.6	101

RMS values. MCB, miniature circuit breaker; I_n, nominal current of OCPD; t_{req}, maximum tripping times required by [16]; $I_{a,min}$, minimum fault current in order to achieve tripping within t_{req}.

Fig. 4 *CDF of initial fault current I_F per islanding scenario ISc defined in Table 2*

Fig. 5 *Simulated oscillation of the fault current I_F (RMS) in an exemplary case of desynchronisation. MCB: miniature circuit breaker*

Fig. 6 *Empirical probability of a desynchronisation for single-phase faults in the islanding scenarios ISc1 to ISc3 of increasing IIDG diversity*

Fig. 7 *Simulated angular difference of IIDG voltage reference angles in case of desynchronisation ($t_F = 3$ s) for different IScs and fault types*
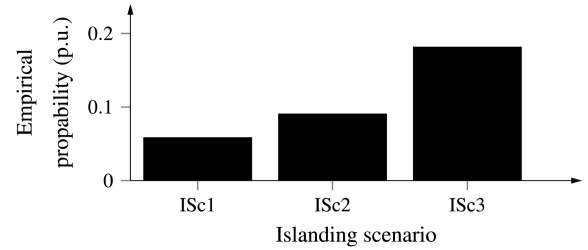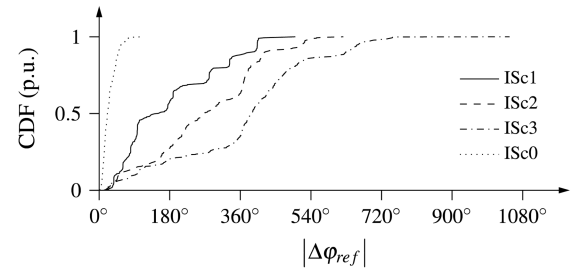
3.2 Effects of IIDG transient stability during faults

The required OCPD tripping times are decisive for the influence of the IIDG' transient stability on overcurrent protection dependability during the further course of the fault. Transient stability is judged based on the development of the difference $\Delta\varphi_{ref}$ between the IIDG' positive sequence voltage reference angles over time (refer to [7]). A loss of transient stability or desynchronisation is here referred to as a situation of continuous growth of $\Delta\varphi_{ref}$ during the fault. Synchronism during faults is here referred to as situation where $\Delta\varphi_{ref}$ settles to a limited value resulting in a steady-state system.

A non-linear correlation over time exists between the angular difference of the injected fault currents and that of the voltage references $\Delta\varphi_{ref}$ for larger angles in case of a loss of transient stability (refer to [7]). Fig. 5 exemplarily shows the simulated effect of a loss of transient stability on the fault currents at the OCPD location. The effective fault current $I_F(t)$ shows a periodic oscillation due to a partial extinction of the IIDG currents. The effect is not decisive for designated tripping times smaller than or in the range of the droop control decoupling time delays. It becomes critical for larger designated tripping times, especially when the fault current minima fall below the required tripping current $I_{a,min}$.

3.3 Influences on transient stability during faults

Relevant mechanisms and factors are identified in case of three-phase symmetrical faults, coming close to stability criteria and quantifying the development over time (refer to [7]). In contrast, only influences are identified on the probability of a loss of transient stability and the development over time in case of single-phase faults. Reasons are a more complex system structure with increased IIDG interaction areas and the widespread variation of parameters performed. Relevant influencing factors on transient stability for single-phase faults are identified as follows (for details refer to [7]):

- CLMs used
- Degree of inter-IIDG CLM diversity and structural diversity (IIDG3 versus IIDG4) (Figs. 6 and 7)
- Power calculation approach used in droop control
- Small final circuit impedances/faults outside
- Inverse relation of rated maximum current and pre-fault available maximum active power

3.4 Conditions for dependable overcurrent protection

Dependable tripping of OCPDs can be gained for one-phased final circuits in the required time, when a specific minimal cumulated rated current capacity of active IIDG can be ensured. For the devices investigated (Table 4), the following criteria given by formulas (1) and (2) have to be fulfilled simultaneously:

$$\sum_{k=1}^{2} I_{r,k} \geq 1,09 \cdot I_{a,min} \tag{1}$$

$$\sum I_{r,\text{IIDG}4} > 0,09 \cdot I_{a,min} \tag{2}$$

These criteria already account for effects reducing the available fault currents as described above. They remain independent of a potential loss of transient stability during the fault duration as long

as the droop decoupling time constants are not chosen smaller than the required tripping times.

Sufficient conditions cannot be sensibly defined for prospective tripping times longer than the droop decoupling time constants (e.g. seconds up to 1 h allowed). Prior to that, measures need to be developed for securely avoiding a desynchronisation of the IIDG during faults. Other protection strategies need to be defined for the typically affected parts of customer installations.

4 Discussion

The derived conditions rely on the assumptions taken and hold for the islanding constellations investigated.

A central assumption is that the IIDG dependably remain connected during a fault (fault ride through requirement) and continuously contribute a fault current. This may be a critical requirement that needs to be verified against technology specific limitations and requirements of the primary energy resource and the DC circuit of the inverter.

Planning approaches or market-based measures need to guarantee the identified minimal cumulated rated current capacities. Reserves should be defined for practical islands.

The available total fault currents may be even lower than identified here, when implicit or explicit voltage limitations of the IIDG become relevant. The latter is to be expected as the simulated voltages of the non-faulty phases in some cases rise up to $\sqrt{3}\,\mathrm{p.u.}$. In the best case, an active design of limiting mechanisms will be done considering their systemic effect. Transient stability during faults will foreseeably be negatively affected due to the introduction of an additional actuator saturation. The further limitation of exchange powers via the healthy phases may lead to an increased probability of desynchronisation. This may also affect constellations where no desynchronisations have been observed in this research (e.g. certain CLM combinations). The development of mechanisms to avoid desynchronisation [6] should be continued as the responsible DSO may not be able to control all influences here identified as relevant in a practical microgrid.

The results and conclusions gained may not be generalised for deviating microgrid setups or IIDG control and limitation structures or parameterisations. The relevant deviations include but are not limited to the following aspects:

- Meshed operation of feeders
- Star point treatment variants
- Number of IIDG interacting
- Transformer-coupled IIDG (e.g. Yd)
- Load scenarios
- Infeed of DG with current source behaviour
- Interoperation of IIDG with rotating machines

Recommendations for IIDG fault behaviour and rating (voltages, currents) are needed. As many islanding constellations and situations are yet to be investigated, we refrain from giving such based on our research solely.

The methodology applied and models developed are reusable for further investigations. The specific assumptions taken have helped to limit the dimensionality of the investigation. Those restrictions may be overcome by widening and detailing the modelling scope, assuming computational power is not a limitation. Parameterisation routines, data extraction automation and analysis criteria need to be specifically adopted. Interpretation does become more complex for higher dimensionality. The methodology is likely not suitable for a day to day use by a DSO. It is rather intended for deriving technical requirements and standards a DSO relies on when planning and operating a microgrid.

5 Conclusions

A DSO needs to choose a protection strategy when intentionally islanding a microgrid. Minimal requirements for the protection of intentionally islanded microgrids should be discussed and standardised between all relevant stakeholders with respect to different use cases, e.g. for backup power supply.

A DSO should be enabled to design an appropriate protection system at the planning stage. The islanded microgrid's fault behaviour needs to become sufficiently predictable and calculable in the future. This is valid for any protection system that relies on protection criteria influenced by the system's overall behaviour (e.g. voltage and fault current based protection). The microgrid's fault behaviour is determined by the interaction of all its participants. One important category is that of IIDGs with grid building functionality. Fault ride through requirements should be defined for such IIDG in IMO, including – but not limited to – maximum tolerable fault durations, minimum and maximum voltages, relative overcurrent rating and interconnection protection settings.

Overcurrent protection is not intrinsically dependable in customer installations when using devices rated for GPO. Measures have to be actively taken in order to enable their usage in islanded operation. The research performed shows the relevancy of the following fields:

i.   IIDG in-detail aspects of control and actuator saturation (design and parametrisation)
ii. Microgrid planning and operation

Requirements have to be derived for IIDG current (reference) limitation, voltage (reference) limitation and IIDG coordination approaches (e.g. droop control) in IMO. To be considered from the DSO point of view are aspects of interoperability between inhomogeneous IIDG as well as constellations involving directly coupled rotating generators.

Microgrid planning needs to ensure the existence of IIDG capable of feeding substantial fault currents into the neutral conductor when investments in dedicated fault current sources are to be avoided. Achievable clearing times are directly affected by the capacity of installed (planning) and active (operation) IIDG due to the typical inverse time–current characteristic of fuses or miniature circuit breakers. Minimal capacities and reserves need to be guaranteed. Their height is influenced by the factors of field 1. Effects of intermediate infeed by uncontrollable sources need to be investigated. Solutions have to be found to achieve sufficient capacities at all times, especially when relying on multiple sources with changing activity. Transient stability becomes a major concern for prospective clearing times in the range of or exceeding the droop time constants. The system's transient stability is highly influenced by the design aspects of field 1, which emphasises the need for further research and standardisation.

The costs or efforts for retaining dependable overcurrent protection in IMO might exceed that of acceptable alternatives. DSOs will need to focus on less selective protection add-on concepts or island shutdown strategies for faults in customer installations in this case. The obligation to take measures for electrical safety remains unaffected.

6 References

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