FEASIBILITY OF AN EFFICIENT ADD-ON PROTECTION SYSTEM FOR A REAL WORLD MICROGRID IN ISLANDED MODE

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ABSTRACT

Designing a reliable protection system for an intentionally islanded Microgrid with multiple grid building units at an early planning stage is a complex engineering task. Necessary investments could be restricted by the help of a supporting planning tool proving the feasibility of using a minimum effort add-on protection system. An according tool is implemented as a proof of concept and is successfully applied to show feasibility in a real world Microgrid. Potentials for further reducing safety margins and complexity of the planning process by a more precisely defined grid building units' fault behaviour in islanded mode become obvious.

INTRODUCTION

In case of a blackout low voltage (LV) Microgrids may offer backup power supply for customers by entering islanded mode [1]. Long term experience exists for islanded mode of operation (IMO) using centrally arranged synchronous generators (SG). Experience needs to be gained when using multiple distributed generators (DG) scattered across a LV distribution system instead. One challenge is the design of a reliable protection system [2]. The distribution system operator (DSO) is responsible for providing an adequate protection system in both grid parallel mode of operation (GPO) and IMO.

According planning tools for GPO are available to engineer Microgrids with a high share of inverter interfaced DG (IIDG) like photovoltaic (PV) units or combined heat and power plants (CHP) [3]. For IMO with grid building by scattered DG a supporting tool for the planning process is not known to exist. This becomes critical when trying to design a minimal protection system for IMO.

While several sophisticated protection concepts for IMO have been proposed [1, 4], they require the replacement of cost efficient fuse protection by circuit-breakers and relays. Furthermore, the requirements assumed should be questioned for the backup power supply use case. Using fuses in IMO requires dedicated highly rated equipment [2, 5]. Trying to sustain fuses for protection in GPO the minimal requirements on add-on measures to achieve a reliable protection in IMO are yet unknown. Assessing the dependability of such an add-on protection at the planning stage with limited available data on equipment is challenging due to uncertainties of e.g. the unit fault behaviour. In addition, a multitude of operational situations needs to be accounted for.

In this paper the feasibility of an add-on protection system concept for islanded operation of a specific real world Microgrid is evaluated. Requirements on protection system performance are discussed and set. A planning tool is developed and successfully applied for engineering the add-on concept. The resulting concept is shown to be feasible within the capabilities of the tool.

IREN2 STUDY MICROGRID

The IREN2 project [6] investigates a real world LV Microgrid located in southern Germany. Six feeders originally fed by two separate transformers in GPO have been joined to form the Microgrid topology in fig. 1 fed by only one busbar. Customer loads are installed in the red, blue, orange and magenta feeders only. Only in these feeders customer owned PV units (450 kWp in total) are installed. Protection at their interconnection point in GPO is implemented according to [7].

Due to reserve capacities for backup supply of adjacent LV grids and increasing integration of DG several feeders (yellow, green, red, blue, magenta) use parallel cables.

Feeder protection in GPO is accomplished by NH-fuses ranging from 125 A up to 500 A. Selectivity is ensured by nominal fuse current grading. Protection of customer installations in GPO is done by fuses (e.g. 50 A NH-fuses in house connection boxes) and selective main circuit-

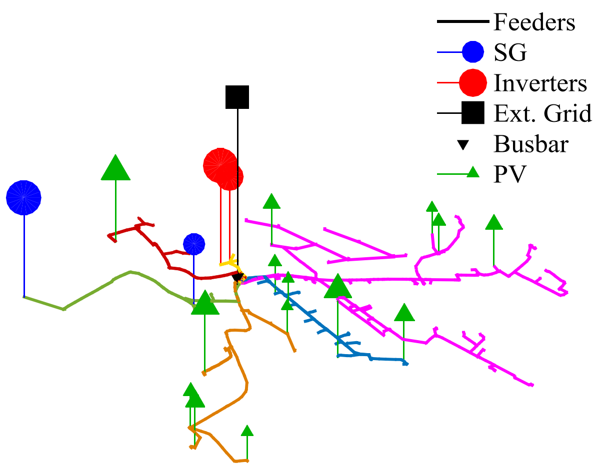

***Figure 1**: IREN2-Microgrid topology and location of power supplying units. Marker size reflects rated powers.*

breakers near the metering units. Final circuits are typically protected by miniature circuit-breakers (MCB, e.g. 16 A, characteristic B), rarely by fuses. Those and sometimes additional residual current devices ensure fault clearing within the required 400 ms. Outside final circuits the maximum fault clearing times required range from seconds up to one hour.

Four droop controlled grid building units for IMO are integrated in the IREN2 Microgrid. Two directly coupled SG with rated powers of 100 kVA and 500 kVA are installed in the green feeder (fig. 1). Two IIDG are placed in the yellow feeder (fig. 1). One back-to-back inverter has a rated power of 500 kVA. One battery storage converter has a rated power of 240 kVA. Protection at the interconnection point in GPO is according to [7] and is designed for IMO in this paper.

The Microgrid can be isolated from the upstream grid. It can be further sectionalized in two parts by a circuit-breaker. The island may be operated as a whole or may be restricted to the green and yellow feeders. Those are without customers, PV or CHP but integrate all grid building units. The relay characteristics of the sectionalizer are to be defined.

PROBLEM FORMULATION

The central problem is to design, parameterize and prove the feasibility and reliability of a cost efficient but technically sufficient add-on protection system at the planning stage of a Microgrid to be intentionally islanded. Subproblems accompanying this process are:

- definition of protection performance requirements
- large scale variability and variants (tab. 1)
- lack of planning tools for islanded Microgrids
- modelling burdened by limited data availability
- classical worst-case scenarios no longer valid in IMO

REQUIREMENT ENGINEERING

Basic requirements on the protection system in GPO are defined by e.g. national standards. Degrees of freedom (e.g. degree of selectivity, speed exceeding basic requirements) are here referred to as performance requirements. These are individually specified by the responsible DSO but follow established practices.

In IMO basic requirements apply identically to GPO. Performance requirements need to be tailored to the applying use case. A fault inside an island for backup power supply may be seen as a second contingency allowing less selectivity. This lowers the number of protection elements necessary for IMO and thereby the costs.

While damage to equipment is desirable to avoid, the need for a transient stable ride through of the island as a whole for each fault is questionable. This lowers the requirements of the speed of the add-on system.

In terms of cost efficiency the add-on approach motivates to preserve as much as possible of the existing protection system elements and functionality. As a result the interference of the responsible protection systems for GPO and IMO should be minimized. Only unwanted operations can be tolerated in contrast to failures to operate.

The protection requirements for IMO defined in the IREN2 project are given by tab. 2. Therein, protection of the grid itself and protection in customer installations is differentiated.

***Table 1**: Variability and variants at the planning stage.*

source	variability & variants
operational	- grid parallel / islanded operation - active set of grid building units (type, max. power) - PV & CHP infeed situation - consumer load situation - fault location, type & impedance
degrees of freedom and uncertainties at planning stage	- grid topology - extend of islanded grid - final ratings (units, cables, etc.) - final parameters (e.g. SG) - protection system solution candidates - fusing scheme - relay protection criteria & parameters - control design & parameterization - actuator saturation design & parameters

***Table 2**: IREN2-specific protection performance requirements.*

prior-rity	feeders	customer installations
high	- reaching a secure state - sufficient speed to avoid damage or hazards	- dependable tripping - speed according to standards
…	- low interference with GPO protection	
	- sufficient speed to avoid loss of transient stability	
low	- selectivity	- selectivity

METHODOLOGY AND MODELLING

Tool supported planning process

Due to the variability and variants at the planning stage the engineering (design, parameterization and verification) of the add-on protection concept shall be based on calculations using an adequate planning tool (fig. 2).

Ideally, an electromagnetic transient or phasor simulation of the island would be used. Still, due to missing information, especially for aspects of grid building units like control and actuator saturation structures and parameters, it would be possible to model the fault behaviour of an arbitrary island but not the specific IREN2-island. Instead, a steady state fault calculation based tool for IMO is developed in extension of a tool for GPO [3]. Missing information is dealt with by modelling assumptions. Critical assumptions can be clearly communicated, discussed and investigated by variation studies. The tool (fig. 2) allows for massive scenario calculations using partially default and partially Microgrid specific models. Models applied and assumptions taken for the IREN2-Microgrid

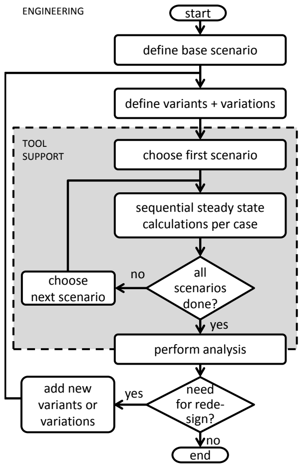

***Figure 2**: Flowchart of the protection planning process utilizing the developed planning tool.*

are given in the following. Such considerations will need to be done by the engineering personal.

IREN2-Microgrid component models

The upstream grid in GPO, feeder lines, transformers, faults and the earthing system are modelled in equivalence to [3, 8] by default models.

The two SG are modelled by their default Thévenin equivalents. Due to the fault durations up to several seconds the effect of changing impedances over time is approximated by consecutive calculations with subtransient, transient and steady state impedances respectively. The influence of the generator control is accounted for by calculating several variant models reflecting different assumptions regarding the control behaviour.

The two grid building inverters are specifically modelled based on manufacturer interviews and discussions. They are represented as controlled symmetrical voltage sources coupled via Dyn5 transformers. Current limiting happens by reduction of the internal reference voltage and is modelled accordingly.

Customer loads are not modelled as their effect is assumed to be neglibale due to the low residual fault voltages expectable in islanded mode.

Modelling of the interaction of PV and CHP with grid building units in islanded mode remains as future research work. In the first field test of the IREN2-island the frequency will be set to 52 Hz in order to deactivate PV and CHP by means of their over frequency relays.

Protection element models are applied ex-post on the calculated values. Tripping events lead to sequential calculations until the fault is fully cleared. Fuses are modelled by their tripping time-current curves. The relay models contain algorithms based on the basic frequency components calculated.

IREN2-Microgrid system modelling

The IREN2-Microgrid is modelled by about 600 nodes and edges. It is assumed to be either in GPO or in stable IMO. Transitions between modes are not in focus.

The component models developed for IMO allow investigating grid building scenarios with single grid building units and combinations of synchronous generators. Due to limited information available on the inverters' fault behaviour further combinations cannot be calculated.

Due to the usage of a steady state calculation approach transient stability of the grid building devices needs to be assumed during a fault in IMO. This results in a best-case investigation in terms of overcurrent criteria and a worst-case investigation in terms of undervoltage criteria.

RESULTS: IREN2 PROTECTION SYSTEM

The specific application of the planning process in fig. 2 yields the following results for the IREN2-Microgrid.

Fusing Scheme

Aided by the developed tool the new yellow feeder for integration of the IIDG is equipped with fuses for protection in GPO. The fusing scheme of the green feeder is adapted to avoid nuisance tripping after integration of the two SG. Several fuses need to be uprated in order to allow for a full power injection of the SG. Accompanying temporary overloading of cables is accepted for the field tests by the DSO. Due to the SG locations at the remote feeder end, selectivity in GPO is partially lost. This also holds for the yellow feeder. The resulting fusing times for faults located on feeders in GPO are given by the cumulative density functions (CDF) in fig. 3a. These clearing times require coordination of the add-on protection for IMO and the fusing scheme for GPO. The former should not trip in GPO. The short circuit currents observable for faults in GPO given by fig. 3b illustrate the high ratings necessary when completely replacing fuse protection by breakers.

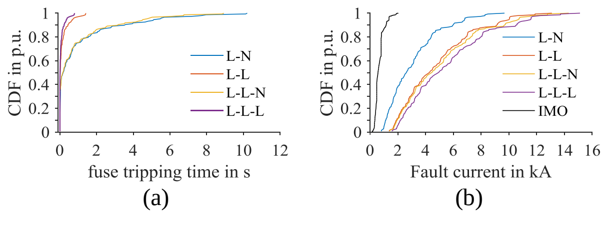

***Figure 3**: CDF of (a) fuse tripping times and (b) fault current amplitudes in GPO in dependence of fault type (max. IMO fault currents given for comparison).*

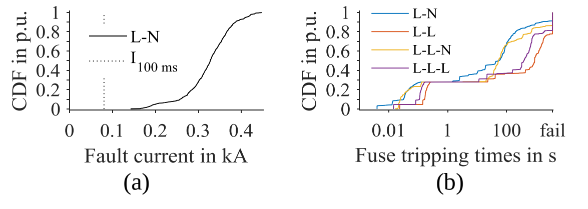

***Figure 4**: CDF of (a) expected fault current in IMO for end of single phased final circuits fault (b) tripping times of fuses in house connection boxes in IMO.*

While faults in final circuits during IMO will be prospectively cleared by the MCB within 100 ms (fig. 4a), tripping of fuses in house connection boxes may fail even when assuming long term stable fault ride through of the island (fig. 4b). Those faults are cleared unselectively by the following IMO add-on protection system.

Minimal Add-On Protection Concept

Design and Coordination

Protection concepts suggested for IMO of LV Microgrids are typically voltage criteria based [1, 4]. In comparison to tab. 2 higher requirements in terms of speed and selectivity are typically assumed. Usage of directional time-grading is often suggested. For GPO (directional) overcurrent protection is suggested to be used in parallel. Relatively complex algorithms need to be implemented and parameterized in multiple relays. Breakers need to be highly rated due to the expected currents in GPO (fig. 3b). To the best of the authors' knowledge, according relays or breaker-relay combinations are not readily available at the market.

Due to the requirements specified a non-directional voltage based tripping criterion is chosen for IMO of the IREN2-Microgrid (fig. 5). Undervoltage detection is performed per phase against the neutral conductor. In dependence of the fault type and location, grid building scenario and the assumptions on generator and inverter control not all fault cases may be reliably detected by low phase voltages. An additional asymmetry criterion k_2 is therefore introduced. It is defined as the ratio

$$k_2 = V^-/V^+$$

of negative (V^-) and positive (V^+) sequence voltages. Nuisance breaker tripping in a deenergized grid is avoided by a minimum current criterion [1]. Tripping happens after a time delay without reset of the above criteria. The criteria are applied to the sectionalizing circuit-breaker and at all grid building unit interconnection points. GPO protection remains unchanged.

Coordination is achieved by time grading:

1. selective tripping of fast overcurrent protection devices (e.g. final circuits, customer protection)
2. partially selective operation of sectionalizing breakers after a defined time delay
3. unselective shutdown of grid building units

The longest tripping delay is used for grid building units. Breakers inside the island act faster but are sufficiently delayed to allow fuses in final circuits to operate reliably and avoid interference with fault clearing by fuses in GPO.

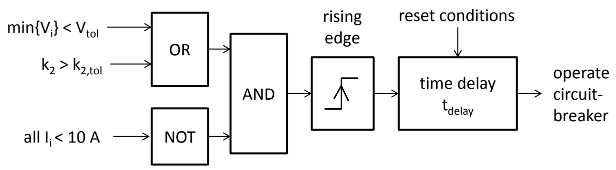

***Figure 5**: Protection criteria applied in relays for IMO.*

Parameterization and Verification

Parameterization of the voltage and asymmetry criteria is done based on variation studies as discussed above. Considering the worst-case results over all grid building scenarios, fault locations, types etc. and applying reasonable safety margins the settings in Tab. 3 are proposed.

***Table 3**: Voltage criteria and time delay settings in IMO.*

protection element	V_{tol}	$k_{2,\mathrm{tol}}$	t_{delay}
circuit-breaker at busbar	0,8 p.u.	0,2 p.u.	2 s
all grid building units	0,8 p.u.	0,2 p.u.	3 s

Fig. 6 shows the calculated criteria values in IMO across all variations performed. A non-detection zone (NDZ) results from the parameter settings in Tab. 3.

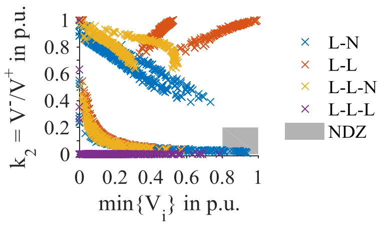

***Figure 6**: IMO protection criteria values across all variations.*

Cases inside the NDZ are restricted to line-neutral faults in grid building scenarios with active inverter coupled units. Due to the Dyn5 transformer coupling relatively high currents can be fed onto the fault. This enables successful fuse tripping within 32 s even in IMO (fig. 7a). The IMO add-on protection system therefore relies on the GPO fuses as well.

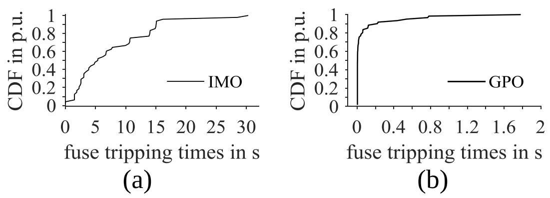

***Figure 7**: CDF of fusing times required (a) in IMO for faults inside NDZ of voltage based criteria and (b) in GPO with nuisance tripping of IMO protection criteria.*

The minimum time delays in Tab. 3 originate from the coordination of the IMO voltage criteria with GPO fuse tripping (outside the NDZ). Full discrimination is possible even for tripping times lower than the maximum fusing times in GPO (fig. 3) as those are associated with low phase voltage drops and low negative sequence voltages at the IMO relay locations. A few seconds allow for successful discrimination and might even enable a transient stable ride through of the overall system (fig. 7b).

Implementation

While the utilized Siemens 7SJ82 protection relays are oversized, they offer the necessary functionalities for efficiently implementing the designed protection criteria in IMO as a proof of concept. Those criteria may be ported to economically suiting devices later, not available at the market yet.

An undervoltage protection function (ANSI 27) is used for the voltage criterion ($\min\{V_i\} < V_{\mathrm{tol}}$). The minimum current condition is checked by a sensitive overcurrent protection stage (ANSI 51). The voltage asymmetry criterion ($k_2 > k_{2,\mathrm{tol}}$) and the logical operations are custom-tailored utilizing the device's programming capabilities.

The implementation has been unit tested in the laboratory and in the field and operates as expected.

DISCUSSION AND OUTLOOK

Feeder Protection

The developed planning tool enabled redesigning the fusing scheme for GPO. As most of those fuses will not operate in IMO, nuisance tripping of the GPO feeder protection system is avoided. By implementing sufficient time delays nuisance tripping of the IMO protection system is avoided in GPO. Protection criteria for IMO were designed, parameterized and coordinated between each other and towards the GPO protection system aided by the developed planning tool. No inner adaptions of the grid building units needed to be assumed for a design fulfilling the defined requirements. The criteria could be successfully implemented in a state of the art relay.

Future field tests will reveal the validity of the modelling assumptions and will give helpful insights for implementing grid building scenarios not modelled so far. Furthermore, the tests will show whether the grid building units will ride through faults in IMO until the successful tripping of the designed add-on protection concept or rather trip beforehand – which would be acceptable. Further tests will clarify the preconditions of operating PV and CHP units in IMO and in how far their intermediate infeed does affect the protection concept developed.

Protection of Customer Installations

For final circuits with tripping times less than 400ms the calculations show the feasibility of using conventional overcurrent protection devices. This is in accordance to simulation based variation studies in [9]. Results for fault locations behind house connection boxes suggest the potential to trip the according fuses, too. Still, it is known from [9] that a loss of transient stability for faults lasting a few seconds may burden dependable tripping. Future field tests will clarify the validity of the assumptions taken, the fault ride through capability of units and the effects of intermediate infeed.

CONCLUSIONS

A minimal effort voltage based add-on protection concept for the islanded mode of operation (IMO) of the IREN2-Microgrid has been shown to be feasible.

Proving the reliability of a minimal IMO protection system at the planning stage requires a planning tool as classical worst-case situations are no longer valid and operational variations and uncertainties need to be considered. A highly automated proof of concept planning tool has been implemented and successfully applied. It helps efficiently narrowing down sensible protection criteria and parameterizations.

The dependability of such a planning tool relies on how exact the grid building units' fault behaviour can be modelled. Hard to come by details of controllers and actuator saturation, especially current limitation of inverters, may be critical. Operational variability and some uncertainties at the planning stage may be dealt with by variation studies. Still, a predominant influence of the necessary assumptions burdens proving feasibility of add-on protection systems or even makes it impossible. Therefore, either technical standards should be developed that narrow down the unit fault behaviour or unit manufacturers should be required to provide specific models for planning purposes. Field tests under way will verify or reject the assumptions taken during the modelling process of the IREN2-Microgrid.

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