TOWARDS EFFICIENT RULES FOR QUANTIFYING THE IMPACT OF DISTRIBUTED GENERATION ON THE FUNCTIONALITY OF TRADITIONAL DISTRIBUTION PROTECTION SYSTEMS

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ABSTRACT

Though traditional distribution protection systems may be endangered in their functionality by integrating distributed generation, rules for efficiently assessing their functional reserve are not available yet. This lack of knowledge on problem potentials may lead to extensive premature and unsystematic investments if overestimated or risking dangers and severe damages if ignored. We suggest a complex concept for developing simple rules to efficiently estimate single protection systems out of a complete asset. Our feasibility studies reveal challenges and some promising first methods and results.

INTRODUCTION

Traditional electrical distribution systems (DS) are most commonly operated radially and fed by a single source. In case of a short circuit (SC) or an overloading situation a radial overcurrent will flow on one single path. A traditional distribution protection system (DPS) is able to observe and distinguish any abnormal system state of the DS by this criterion. Appropriate rating and coordination of the DPS leads to reliable and fast operation of protection elements and allows for selective tripping of only the smallest possible part of the grid around the fault. Rating and coordination are done efficiently by state of the art methods.

The integration of distributed generation (DG) facilities in traditional DS may alter their system states qualitatively and quantitatively from those classically assumed in DPS design. Several potential problems of traditional DPS due to these changes are reported in literature [1,2,3]. While momentarily problems of power quality due to DG are more pressing, the increasing integration of DG will promote protection problems. The design of concepts and solutions for the developing duties and market opportunities of DG may even push on the situation.

The knowledge on the upcoming changes in DS states and resulting protection problems is yet limited. Rules for efficiently assessing the functional reserve of traditional DPS are also lacking. The infeasibility of detailed and time consuming simulative investigations in every DS may lead to unfavourable consequences:

- Ignoring the developments or taking technically inappropriate measures means risking in some cases a lowering of the quality of supply only and in other cases extensive damage to DS components, DG facilities or even animals and humans.
- Unwanted restriction of DG installation or of DS operation (e.g. automatic reclosing) to avoid unknown limits of the protection system functionality influenced by DG may result, annulling economical, ecological and energy political goals.
- Unnecessary and costly investments in primary infrastructure or installation of overkill protection system and communication solutions.

Widely and easily applicable and efficient tools need to be developed to identify the functional reserve of traditional DPS and thereby the necessity of measures in single DS and the overall asset. They will also help developing appropriate solutions for those cases.

CHALLENGES AND REQUIREMENTS OF RULE DEVELOPMENT

The rules to develop shall fulfil the following requirements in order to make them beneficial:

- Most general applicability and validity
- Efficiency of application
  - Minimal amount and good availability of input data
  - Limited complexity
  - Resemblance to known procedures
- Conservative assessment, but with known accuracy

A concept and methodology to derive such needs to:

- deal with a large variety of investigative cases,
- provide means to quantify DS states and DPS reactions in all these cases and
- derive rules from those calculations by analysis.

Variety of cases

It is unknown yet, which protection problems will be relevant under what exact circumstances. The lack of practical experience with high penetration scenarios leaves the chance of unforeseen new system states in DS and a priori unknown problems in traditional DPS. Therefore a large number of problem cases needs to be investigated.
These problems may occur in DS of different topologies and component properties. A number of typical traditional DPS concepts have established which leave degrees of freedom to some extent. Faults may occur all over the DS. To gain most general applicability, all those combinations need investigation.
The biggest impact is due to the DG integrated into these DS. Their placement and rated power may differ as may their technology and type of interconnection to the DS. Numerous scenarios of penetration levels and mixtures can be imagined. Their layout decides on the plausibility of

protection problems. Assumptions on future network planning potentials enable consideration of high penetration scenarios at all. Future market opportunities and duties like ancillary services may lead to new dynamic and static DG behaviour and should be considered.
While for investigations on DPS without DG one can concentrate on well known worst-case situations, DS with high DG penetration bear a higher complexity. A yet unknown number of components needs to be considered simultaneously in their systemic influence. Missing experience makes it difficult to identify worst and best case situations. Furthermore, due to the volatility of DG infeed and other factors, a range of those situations may coexist.

Quantification of DS states and DPS reactions

The new multi-source character leads to an explosion of necessary model size and parameter numbers in each single case. Reductions are limited by the lack of reliable worst and best case knowledge. New methods for identifying such and for quantifying sensitivities need development.
The modelling approach for calculating DS states and DPS reactions should depend on the requirements of the case of investigation and be as simple as possible.
Quasi-static calculation approaches will yield satisfactory results e.g. in load flow calculations or short circuit (SC) calculations for directly coupled electrical machine DG. Under- or overestimation due to uncommon dynamic behaviour may though result [4]. Validated quasi-static models for inverter coupled DG or other new grid components are not publically available for SC calculations. Coverage of expected sequential tripping events in traditional DPS by those methods also needs validation.
While dynamic modelling and time domain simulation will be the keys to overcome these obstacles, a brute-force detailed modelling will rather not be successful. Developing rules is infeasible due to the necessary model size. Our feasibility studies show an explosion of simulation time for even a few DG. The parameter explosion due to the detailed models leads to highly specific results with questionable possibility of generalization.
Furthermore, dynamic SC models of inverter coupled DG of traditional DPS elements are not publically available. The accuracy of developed models remains to be investigated.

Derivation of rules by analysis

The development of rules needs to assess the DPS reactions in the cases simulated. For this, the requirements posed by all sides need mapping.
The requirements themselves will develop. Problematic example is the definition of new systemic coordination requirements with influence to selectivity and quality of supply. The complexity will generally increase due to the new interrelationship of formerly independently rated and coordinated parts of a DPS.
There remains the challenge to formulate the rules in a way to make them efficiently applicable by reducing necessary input data and increasing universality as far as possible.

SUGGESTED CONCEPT AND METHOD

Fig. 1 visualizes our proposed concept for developing the desired efficient rules. Greyed out steps will be explained in the following feasibility studies.

Starting point is an a-priori definition of expected scenarios, cases to investigate and foreseeable protection problems. Besides a further literature review we propose protection expert interviews as a source of cases and prioritization.

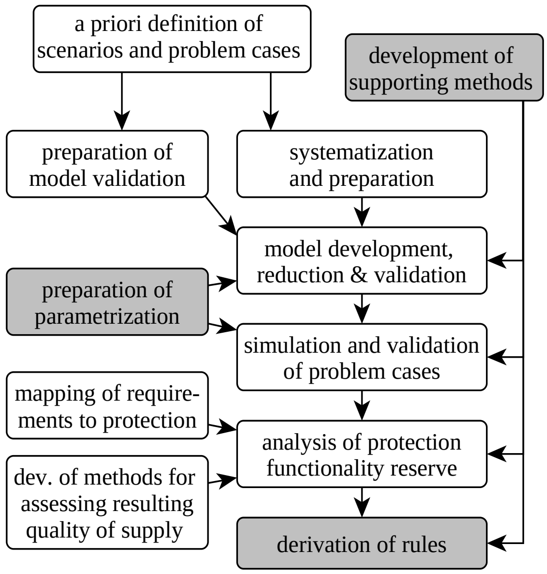

Fig. 1: Suggested concept. Arrows show dependencies.

We suggest preparing and systemizing the investigations by defining modeling and data requirements and developing a data model for structural and non-structural parameters of the case, models and methods used and investigative results.

The model development we propose aims at providing validated models of minimal size and complexity with controllable accuracy. Subject matters are component and system models, namely all classical DS components, DPS and DG.
Cases coverable by quasi-static models already provide small component model complexity for calculation. Other cases require development of new models as described before. For those we suggest a bottom up dynamic modelling approach. We firstly will model components like single DG in detail. Precision and validity of those we will validate by laboratory or field testing. Application of reduction techniques will reduce model size and complexity and parameter amount to an extent of acceptable and quantifiable accuracy and feasible calculation time. When possible and for those studies reasonable, we will derive quasi-static equivalents. Dynamic models of traditional DPS elements and DG side protection systems will be necessary for dynamic investigations and the identification of reduction criteria for other components and systems by sensitivity analysis.
Based on the validated models we will develop DS models of increasing component and DG extent, based on chosen example cases. We will validate their results by testing in laboratory mapped or real DS. The increasingly sized system models need controlled model reduction to enable the desired amount of parameter studies.

Simulation and validation will deal with single investigative cases but also with combinations of those in order to identify ameliorative situations. Besides, we will try to identify new protection problems due to unforeseen systemic reactions. The variation of structural and non-structural parameters will lead to a large number of simulations. The DS states and DPS reactions simulated shall again be validated by sample testing.

We will prepare the validation by designing and implementing laboratories, choosing convenient real DS or DG-sites and developing methods for the validation process.

To enable assessment of DPS functionality we will map the existing and scenario-based future protection requirements of single participating components into a complete DS's requirement space. Those related to speed, sensitivity and reliability need to be completely fulfilled to speak of a proper technical functionality. This lays one basis for the definition of a DPS's functional reserve.
The requirement of selectivity is directly related to the systemic reaction of the DPS and mainly affects the quality of supply in a DS. It is no longer easily obvious, what selective traditional DPS behaviour is or which behaviour means optimal quality of supply. We suggest developing methods to assess the DPS selectivity's effect on the quality of supply as a second basis for the definition of a traditional DPS's functional reserve.

The analysis of the simulation result will yield the traditional DPS functionality reserve in identified problem cases. It will consider proper technical functionality and achievable selectivity. The validity of the identified borders of functionality we will prove by provoking them in the laboratory context.

FEASIBILITY STUDIES

We identified blinding and sympathetic tripping as possible protection problems in non-islanded DS. Blinding of feeder protection happens by a reduction of the minimal SC current supplied by the grid due to DG installed to the feeder. Sympathetic tripping is an unselective tripping of healthy feeders due to their DG' contribution to a fault on a neighboured feeder. We concentrated on a low voltage DS with current-limiting fuses. The DG considered are directly coupled synchronous generators (SG).

Example case modelling

We model the DG as a concentrated SG as a worst case approach using IEC 60909. We model fuse behaviour separately. Generator and interconnection protection are neglected due to the assumed scenarios. Fig. 2 shows the parameters of the blinding case and fig. 3 those of the sympathetic tripping case, both after including worst-case knowledge.

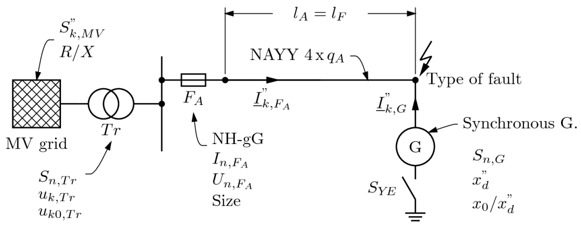

Fig. 2: Blinding of feeder protection modelling

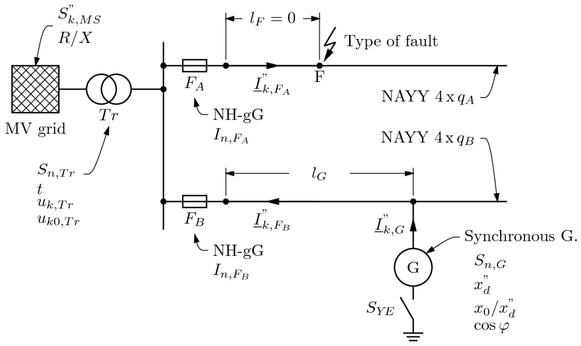

Fig. 3: Sympathetic tripping of feeder modelling

Methods developed

Parameterization and calculation

We identify for every of the N parameters the typical range of values to be found in German DS and choose at least three point of it. The Cartesian product of all parameters' data-points defines then the superset of all possible constellations and the number of calculations to be done.

Sensitivity analysis

We perform an explorative sensitivity analysis in the complete parameter space. Setting N-1 parameters to specific values, we determine the influence of the variation of the Nth parameter on the investigated output variable measured by the maximal span width. We do this for all combinations of the N-1 parameters. Ordering creates a cumulative distribution function (CDF) of the influence of the Nth parameter. Application for all N parameters yields N CDFs, which may be compared like e.g. in fig. 4.

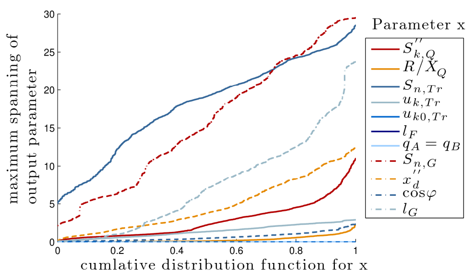

Fig. 4: CDF for sensitivity comparision of parameters x

This procedure allows for a ranking of parameter influence.

Parameter reduction for rule development

We developed an algorithm to support choosing parameters for rule formulation. Besides maximum influence it considers the amount of resulting uncertainty by left out parameters and if the resulting graphical formulations allow for a distinguishable display of the results.

Current status of the resulting rules

As a first approach we suggest to use families of curves as a well known tool in engineering sciences.

As traditional DPS will have been parameterized before integration of DG, the reduction ratio of the SC current with DG to without DG is relevant for assessing the functional reserve in the blinding case. Fig. 5 shows the calculated drop in case of the critical minimal one-phased SC current.

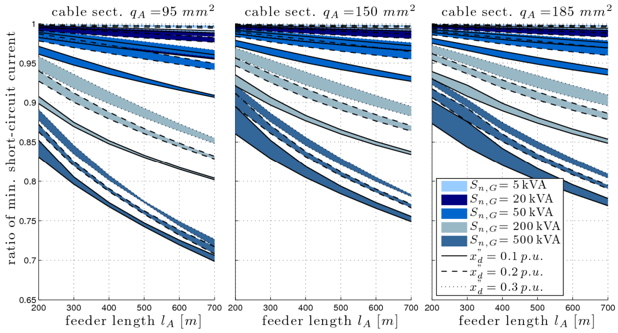

Fig. 5: Relative drop of SC current in feeder fuse due to blinding effect. For parameters compare fig. 2

The bandwidth of the curves reflects the influence of the neglected parameters. Fig. 6 similarly depicts the calculated critical ratio for different fuse ratings and other parameters.

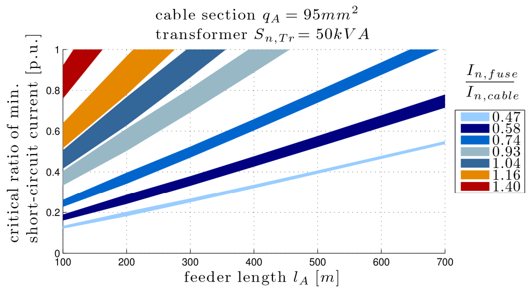

Fig. 6: Critical drop of SC current in feeder fuse

By first using fig. 5 to determine the actual drop ratio and then using fig. 6 to determine the permissible drop, an efficient assessment of the installed fuses' functional reserve can be performed. As you can observe, we gain a reduction to 43% of the original parameters.

In the case of sympathetic tripping the ratio of the SC currents trough the two feeders' fuses is the most relevant criterion for assessment of selective behaviour. Fig. 7 shows the permissible ratio for a selective tripping of the fuse in feeder A, expressed as an angle resulting from the tangent of the ratio of the SC current in fuse A to fuse B.

Most influencing is the ratio of nominal currents of the fuses installed. We identified the three-phased fault as worst-case and give the calculated angles in fig. 8.

If the identified maximum angle from fig. 8 does not exceed the minimum of the tolerable angle for a given fuse ratio in fig. 7, selective behaviour of the fuses is achieved.

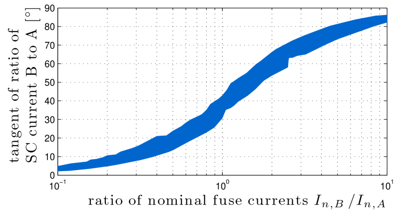

Fig. 7: Maximum angle of SC current ratio for selectivity.

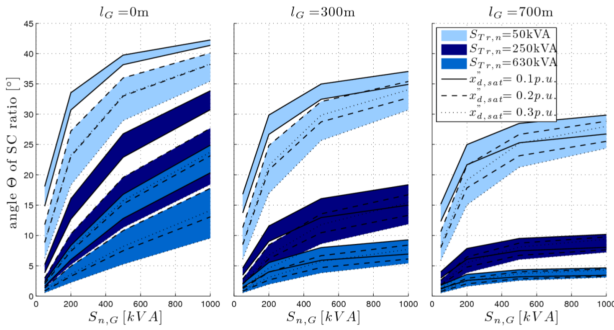

Fig. 8: Resulting angle in case of a three-phased fault. For parameters compare fig. 3

CONCLUSION

Based on the insights from the feasibility studies performed we have developed a concept for deriving rules to efficiently assess the functional reserve of traditional DPS in DS with future high penetrations of DG. Though easy to model problem cases have been investigated as a starting point, we already needed to develop new methods to derive a first suggestion of a rule formulation. The discussed limits of the used approaches lead to the complex concept we suggest. It becomes obvious that the aim of efficient rules demands a high effort of development.

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