DISTRIBUTED GENERATOR STATUS ESTIMATION FOR ADAPTIVE FEEDER PROTECTION IN ACTIVE DISTRIBUTION GRIDS

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ABSTRACT

This paper proposes a framework for adaptive feeder protection in distribution grids with a high amount of distributed generators (DGs) installed. The scheme adapts the feeder protection relay settings according to the changes in the connection status of those DGs that have a significant impact on the fault current. The core of the method consists in the identification of the connection status of the DGs using an iterative modified state estimation (SE) program. The approach is illustrated using a realistic 31-node distribution network model.

INTRODUCTION

The massive penetration of distributed generators (DGs) into the distribution networks may lead to bi-directional power flows and have a serious impact on the system contribution to the fault current. These effects may cause severe troubles for the protection of the distribution feeders such as sympathetic tripping i.e. the mal-tripping of a healthy feeder due to reverse currents caused by a fault on an adjacent feeder and the blinding effect i.e. the failure or delayed operation of protection relays due to reduced fault current seen at the start of the feeder [1-2].

There are many solutions suggested in literature to account for these problems, for example:

In [3], the authors propose to solve the blinding effect by changing the relay settings during the planning stage. The problem with this approach is that, in case the DG is disconnected during operation, the fault current values would revert to their previous values while settings stay the same. Overloads may be misidentified as faults.

In [4], the authors propose a transient based protection scheme that divides the distribution system into segments and uses wavelet transformation on current measurements on all branches leaving busbars that separate the different segments, to identify the segment where the fault is located. The method is quite computation-heavy and requires perfect measurements to avoid missing the occurrence of faults.

In [5], a multi-agent system is proposed. In case a fault is detected relay agents send the information to a coordination agent that identifies the fault location and sends it to the configurator agent that chooses which relays need to operate. Coordination between relays is hence done online and selectivity problems are avoided. This method is very dependent on communication.

A very appealing approach to safely accommodate increasing levels of DGs consists in adapting the protection relay settings with the changing operating conditions of the network [2][6].

Identifying the changes in operating conditions, (mainly the status of the DGs) is a challenging task as nowadays most distribution systems are poorly observable. An important step towards the desired concept of smarter active distribution grids consists in the installation of smart meters to consumers. This process has already started in many countries and will significantly improve the real-time load forecast. This would allow for more accurate state estimation (SE) in distribution systems, despite the low level of measurements redundancy. Distribution SE is one method for monitoring the connection status of DGs [7].

This paper builds on this concept and proposes an iterative modified SE program to detect changes in the connection status of the DGs and a scheme to use this information to adapt the protection settings.

OVERVIEW OF THE OVERALL APPROACH

The proposed approach is illustrated in Figure 1 and is divided into two main steps:

- Detecting changes in the status of the various DGs connected to the distribution grid.
- Checking the relay protection settings and adapting them if needed.

The focus of the paper is on the former of these steps by adapting the conventional state estimation formulation to our purpose.

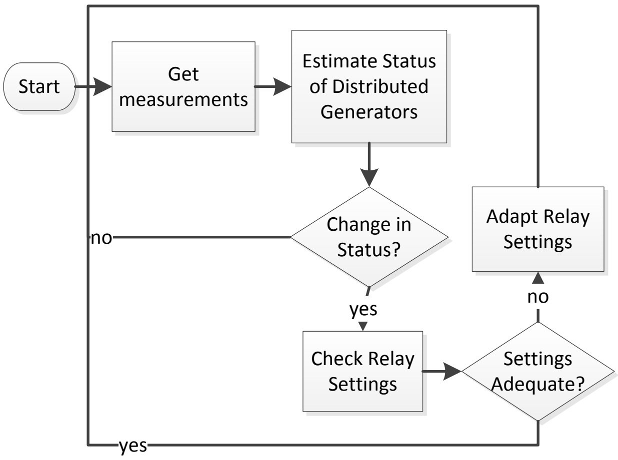

Figure 1: Flowchart of the Overall Scheme

STATE ESTIMATION TO IDENTIFY DISTRIBUTED GENERATORS CONNECTION STATUS

In order to estimate the connection status of the DGs in the context of scarce measurements, the conventional state estimation problem [8] can be extended so as to include binary variables (stemming from the connection status on/off of DGs) and inequality constraints (e.g. active/reactive power limits of DGs) [9]. This leads to very challenging formulations belonging to the class of mixed integer nonlinear programming problems or nonlinear mathematical programming with complementarity constraints. Nowadays there are no reliable and fast solvers for large scale combinatorial generic problems of these classes of optimization problems. An enumerative approach would also be too computationally intensive as for n DGs one needs to run 2^n times a conventional SE program. To overcome these limitations and reduce the combinatorial space a Bayesian hypothesis testing procedure is proposed in [7].

In this paper we use an iterative SE approach which relies on reasonable heuristic rules to identify the DG connection status.

The proposed program calls successively a modified state estimation using an extended vector of states that includes the active and reactive power generation of DGs in addition to the complex voltage vector *x*:

$$x_e^T = [x^T\ P_{DG}^T\ Q_{DG}^T]$$

The measurement vector is given by:

$$z = h(x_e) + e,$$

where $h(x_e)$ is the nonlinear function relating measurements to the states and e is the vector of measurement errors.

Due to a limited number of real-time measurements being available in distribution networks, load estimates and zero injection buses are considered in addition to the active/reactive power flow and voltage measurements. Also included in the measurement vector are the active and reactive output estimates of the DG based on the latest run of the algorithm, as in most cases the connection statuses of DGs do not change dramatically.

The state estimation problem is then formulated using the weighted least squares (WLS) method such that the following optimization problem is solved [8]:

$$minimize \sum_{i=1}^{m} \frac{(z_i - h_i(x_e))^2}{R_{ii}},$$

where R_{ii} is the diagonal entry of the measurement error covariance matrix (the square of the standard variation of measurement *i*).

After an initial state estimation, a check is performed on the results, the normalized residuals of the DG outputs are compared and changes are made to the measurement vector such that:

- If P_{DG} and/or Q_{DG} violate the maximum limits of the generator, their value in the measurement vector is set to those limits.
- If $P_{DG} < 0.85 * P_{min}$, both P and Q are set to 0.
- If the generation output of a DG is not suspected to be false (based on the residuals of the measurements), the control mode of the DG is taken into account:
    - If the DG is set to voltage control, if Q_{DG} is within its specified limits, a voltage measurement is added to the measurement vector with the voltage control setting as its value.
    - If the DG is set to control Q_{DG} at a constant value, the measurement of the reactive power output is set to this value.
- R_{ii} corresponding to the DG output measurements are adjusted based on their relative normalized residuals.

Another state estimation is then performed and the process is repeated until no bad data for the DG outputs is suspected and/or a predefined number of iterations are performed.

The use of the additional information about the DG (P/Q limits and control mode), allow for a more accurate estimation using the limited number of available measurements.

TEST DISTRIBUTION NETWORK

The test distribution network used in the simulations is based on a realistic 31-node distribution grid model provided by CREOS, the electricity network operator in Luxembourg (see Figure 2). Its characteristics are given as follows:

- Voltage Level: 20 kV
- Total feeder load: 12 MVA @ 0.98 PF
- Average X/R ratio: 1.38
- 4 DGs installed at nodes 9, 16, 22 and 30 (see Table 1 for characteristics)
- Voltage measurement at distribution substation (node 1)
- P/Q power flow measurements on lines 1-2, 7-10, 17-21 and 23-26.

Table 1: DG Characteristics

DG	Pmax (MW)	Pmin (MW)	Qmax (MVAr)	Qmin (MVAr)	Control Mode
1	2.24	0.224	0.592	-0.872	V=1pu
2	4.6	0.46	2	-2.4	V=1pu
3	2.24	0.224	0.592	-0.872	Q=0
4	2.3	0.23	1	-1.2	V=1pu

NUMERICAL RESULTS

Three case scenarios denoted A, B and C are presented hereafter. The inputs to each of the cases, the actual values for the DG outputs and the results are presented in Tables 2, 3 and 4.

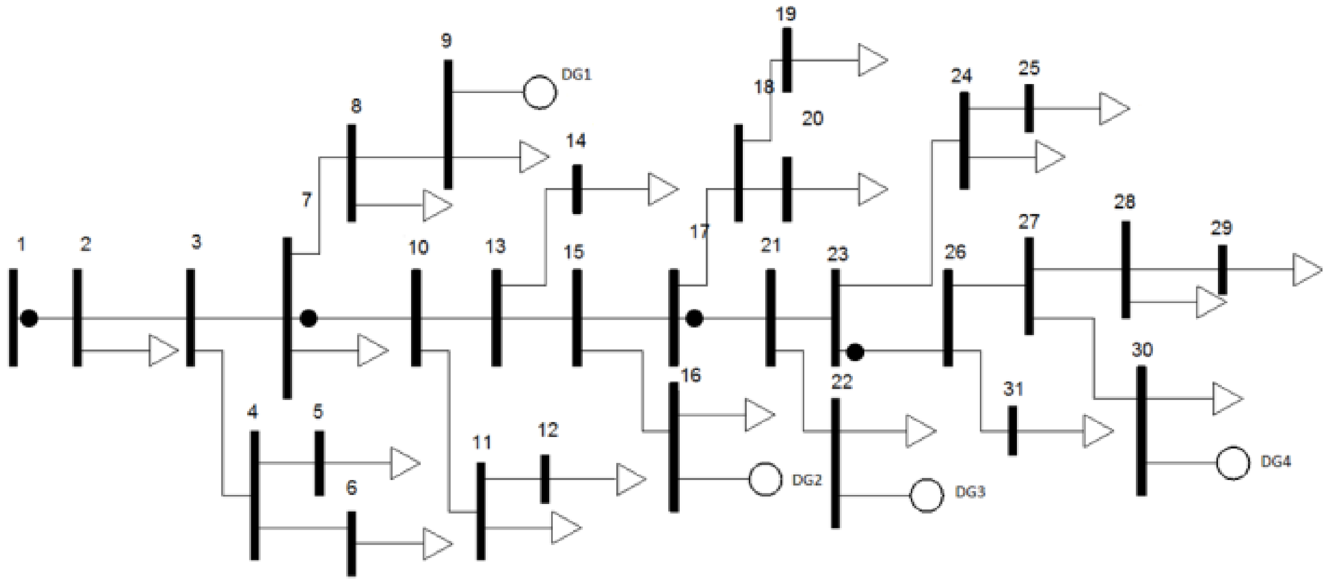

Figure 2 – One Line Diagram of the Test Distribution Network

Table 2: Case A

	DG	Actual	Input	Iter1	Iter2	Iter4	Iter6
P	1	0	1.72	0.07	0.03	0.01	0
	2	4.2	4.2	1.53	2.92	3.89	4.09
	3	0	1.8	0.12	0.04	0	0
	4	1.72	1.72	0.84	1.34	1.66	1.73
Q	1	0	0.59	0	0	0	0
	2	1.72	0.13	0.63	1.2	1.6	1.69
	3	0	0	0.04	0.01	0	0
	4	1	1	0.42	0.67	0.83	0.87

Table 3: Case B

	DG	Actual	Input	Iter1	Iter2	Iter4	Iter6
P	1	1.7	0	0.74	1.19	1.43	1.58
	2	4.2	0	1.59	2.84	3.81	3.97
	3	1.8	0	1.04	1.05	1.14	1.21
	4	1.72	1.72	0.89	1.36	1.61	1.73
Q	1	0.6	0	0.22	0.36	0.47	0.53
	2	0.1	0	0.05	0.09	0.12	0.12
	3	0	0	0.1	0.09	0.09	0.1
	4	1	1	0.33	0.51	0.62	0.67

Table 4: Case C

	DG	Actual	Input	Iter1	Iter2	Iter4	Iter6
P	1	0	1.72	0.98	0.52	0.13	0
	2	0	4.2	2.62	1.33	0.38	**0.05**
	3	0	1.8	0.79	0.29	0	0
	4	0	0	0	0	0	0
Q	1	0	0.59	3	0.12	0	0
	2	0	0.13	0.81	0.41	0.12	**0.01**
	3	0	0	0	0	0	0
	4	0	0	0	0	0	0

Any input information that does not correspond with the actual situation of the distribution network has been greyed out in the table to highlight the bad data.

In Case A, the SE is given information that all the DGs are on, while in reality DG1 and DG3 are disconnected. In Case B, the inputs to SE show that 3 of the DGs are off but in fact all are on. In Case C, the SE has as inputs that only DG4 is off, but all DGs are in fact off.

As shown in the three cases, the state estimation results are improved with each iteration. Except for DG2 in Case C, the correct statuses of the generators were identified for all generators in the three cases after 6 iterations.

The improvement in the results is even more apparent when the voltage profile is studied. In Figure 3, the voltage profiles in Case B, after the first and sixth iterations, are illustrated in comparison to the actual voltage profile.

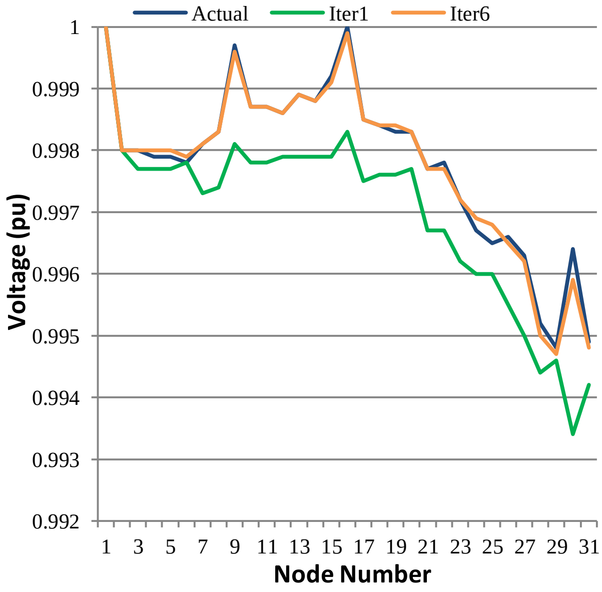

Figure 3: Case B - Voltage Profiles

The use of the additional information about the output limits and control settings of the DGs connected to the network has dramatically improved the SE results.

CONCLUSIONS AND FUTURE WORKS

Preliminary results are encouraging, the approach being able to correctly identify in most cases the connection status of DGs. Expectedly, due to the trade-off between investments and results accuracy, the limited number of additional measurements makes it sometimes difficult to distinguish the correct status for some generators, especially in extreme situations where many changes occur simultaneously. However, although the ambitious goal is to ideally identify the status of all DGs, the main aim is to update the protection settings if needed in the context of minimum investment on additional measurement devices so that the non-identification of the right status of a small percentage of DGs would not require the protection settings change.

As we initialize the DG outputs with the values obtained in the previous run of the algorithm we notice that the larger the number of changes in the connection status of the different DG, the more iterations are needed for an accurate result. Nevertheless this does not cause a major increase in the computational time.

Several aspects of the approach remain to be more deeply investigated:

- Tests how the approach scales to larger distribution systems.
- Different approaches to altering the weights assigned to the measurements to speed up the convergence process.
- In the paper we use, intuitively and depending on DGs location, a small number of additional measurements but future work is needed to minimize the number of additional measurements and determine their deployment in an optimal manner. We shall investigate in particular how the approach scales with the growing number of DGs.

Acknowledgments

This work was conducted at the “Interdisciplinary Centre for Security, Reliability and Trust” (SnT) at the University of Luxembourg as part of the “Reliable and Efficient Distributed Electricity Generation in Smart Grids” (REDESG) project within the “CREOS-SnT Framework Programme”. It is supported by the National Research Fund, Luxembourg (C11/SR/1278568).

REFERENCES

[1] J. Deuse, S. Grenard, M.H.J. Bollen, M. Hager, F. Sollerkvist, 2007, "Effective impact of DER on distribution system protection", *CIRED Conference*, paper 075.

[2] N. Schaefer, T. Degner, A. Shustov, T. Keil and J. Jaeger, “Adaptive Protection System for Distribution Networks with Distributed Energy Resources,” in *10th IET International Conference on Developments in Power System Protection*, 2010

[3] P. Jarventansta K. Maki, S. Repo. “Effect of wind power based distributed generation on protection of distribution network”. *Eighth IEE International Conference on Developments in Power System Protection, 2004*, 1:327-330, April 2004.

[4] M. Popov I. Xyngi. “Transient based protection scheme for distribution grids supplied with distributed generation”. *Proceedings of the 44th International Universities Power Engineering Conference (UPEC), 2009*, pages 1-5, September 2009.

[5] J. G. Rolim P. C. Maiola. “A multi-agent system for protection coordination of radial systems in the presence of distributed generation”. *11th International Conference on Developments in Power Systems Protection, 2012. DPSP 2012*, pages 1-6, April 2012.

[6] I. El-Markabi M. Baran. “Adaptive over current protection for distribution feeders with distributed generators”. *IEEE PES Power Systems Conference and Exposition*, 2004, 2:715-719, October 2004.

[7] A. Simoes Costa, M. Carneiro dos Santos, 2007, "Real-time monitoring of distributed generation based on state estimation and hypothesis testing", *Proceeding IEEE PES Powertech Conference*, 538-543.

[8] A. Abur, A. Gomez Exposito, 2004, Power system state estimation: theory and implementation, Marcel Dekker, New York, USA.

[9] K.A. Clements, P.W. Davis, K.D. Ferry, 1995, "Treatment of inequality constraints in power system state estimation", *IEEE Trans. On Pow. Syst.* vol. 10, no. 2, 567-574.