

## Towards Methodological Refinement of Power System Protection Testing via Statistical Design of Experiments

MIRKO GINOCCHI, THANAKORN PENTHONG AND FERDINANDA PONCI  
*Institute for Automation of Complex Power Systems,  
RWTH Aachen University, 52064 Aachen, Germany*

The growing complexity of modern power systems calls for sophisticated protection functions in order to ensure the correct operation as well as the reliability, quality and security of supply. Testing the protection functions implemented in protection equipment/systems is, hence, a vital activity for ultimately preventing the potentially disruptive consequences of protection failures.

In general, any testing activity requires three main components:

1. **What to test**, i.e., the Device Under Test (DUT), whose ability to operate based on manufacturers' specification is tested under realizable power system conditions.
2. **Where to test**, i.e., the platform over which to conduct the tests, which is usually based on a real-time hardware-in-the-loop simulation test set-up to investigate the DUT behavior under close-to-operation conditions.
3. **How to test**, i.e., the methodology defining which and how many tests to conduct in each experiment, by deliberately varying different factors potentially having an impact on the system response.

In power system protection testing, while the first two components are well established, the testing methodologies are still less mature and quite fragmented, and are thus the focus of our work. Harmonization efforts have been produced by national and international standards, such as the IEC 60255-121:2014 standard [1], which was issued with the intent to address the lack of uniformity among testing methodologies, prevent misunderstandings among stakeholders, and produce a uniform procedure to evaluate and compare performance claims from different manufacturers. The testing methodology recommended by the IEC 60255-121:2014 standard [1] is implicitly based on a (replicated) full factorial design, which may not be compatible with the maximum number of tests that the operator can afford in each experiment. For example, the testing activity performed in [2] based on such full factorial design consisted of almost 100,000 tests; as only 5 tests per minute were possible, this translated into about 40 days of tests.

Power system operators often work in resource-saving contexts, and, not rarely, time/money considerations are adopted to justify the “arbitrary” or “convenient” selection of which and how many tests to perform. Such common practice can be overcome by the statistical Design Of Experiments (stat-DOE), which combines the strength of the classical DOE with the power of the statistical approach to aid in both properly laying out a resource-saving experimental plan and conducting robust statistical analysis of the data.

The stat-DOE was an integral part of the smart grid interoperability testing methodology proposed in [3]. The relevance of the stat-DOE was shown in [4], which applied the methodology of [3] for testing the interoperability of a metering infrastructure. However, in [4], a full factorial design was employed, which quickly undergoes the curse of dimensionality as the number of factors grows.

In [5], it was proposed to integrate the stat-DOE in the power system protection testing especially in resource-saving contexts. In particular, it was practically demonstrated how the stat-DOE can aid in the optimal selection of the tests and in the systematic investigation of the effect of different factors, it was proven the superiority of modern designs over classical designs (such as full and fractional factorial), and replicable guidelines were elaborated for the application of the stat-DOE in the performance testing of power system protection functions.

Leveraging on [5], we go one step further by showing how the stat-DOE can be employed to test the performance of different DUTs coming from different manufacturers. In our work, the DUTs are physical relays where the distance protection function is implemented, the latter being the

power system protection function most commonly adopted in transmission systems. The distance protection function, which is subject of the testing activity in our work, estimates the location of the fault on the transmission line based on the DUT internal fault location algorithm and using current and voltage measurements coming from the field.

Following the recommendations of the IEC 60255-121:2014 standard [1], various factors potentially affecting the DUT performance are considered, such as fault resistance, fault location, fault type and fault inception angle. Special attention is placed on the type of design used for the optimal selection of the tests to conduct, owing to the well-known challenges of time/money limitations often affecting the testing activity. The response measured to quantify the distance protection performance is the DUT operate time (i.e., the interval between the time at which the fault happens and the time at which the relay sends the trip signal). As the interest of the operator is, often, whether the DUT operate time exceeds a pre-defined threshold, the test results are also analyzed in terms of pass/fail outcomes.

By applying the stat-DOE workflow, we show how building a surrogate model of the fault location algorithm can be of practical use to validate the performance claims of different DUTs and hence detect potential internal inconsistencies in a cheap yet robust manner before the field implementation. Also, we demonstrate how the stat-DOE can effectively support the definition of pass/fail criteria based on specific requirements of the transmission system operators.

Although in the first place the purpose of the testing activity is usually not directly related to Sensitivity Analysis (SA), the operator may be interested in identifying which factors mainly drive the degradation of the DUT performance in order to support the definition of further experiments. By interpreting the test results in terms of pass/fail outcomes, we recast the problem into the “factor mapping” SA setting, and we recommend the operator to employ a simple statistical test for identifying the factors to which the DUT performance is most sensitive. If additional experiments are needed, this may instruct the operator e.g., to sample the most important factor(s) at more levels, and/or to neglect those which turned to have minimal impact on the DUT performance.

Overall, the attained results allow us to claim that integrating the stat-DOE into the testing activity of power system protection can overcome the limitations of the existing testing methodologies, and that, at a broader level, it can represent a common and standardized basis for ensuring replicability, robustness and objectivity of the testing activity.

## References:

- [1] International Electrotechnical Commission. Measuring relays and protection equipment – Part 121: Functional requirements for distance protection. 2014.
- [2] A. Novikov, J. Jesus de Chavez, and M. Popov. Performance assessment of distance protection in systems with high penetration of PVs. In *2019 IEEE Milan PowerTech*, 1–6, 2019.
- [3] I. Papaioannou, S. Tarantola, A. Lucas, E. Kotsakis, A. Marinopoulos, M. Ginocchi, M. Olariaga Guardiola, and M. Maserà, Smart Grid Interoperability Testing Methodology. *Publications Office of the European Union*, 2018.
- [4] N. Andreadou, A. Lucas, S. Tarantola, and I. Poursanidis, “Design of experiments in the methodology for interoperability testing: Evaluating AMI message exchange”. *Applied Sciences*, 9(6), 2019.
- [5] M. Ginocchi, T. Penthong, F. Ponci, and A. Monti, “Statistical design of experiments for power system protection testing: A case study for distance relay performance testing”. *IEEE Access*, 12:27052–27072, 2024.

[ Mirko Ginocchi; Institute for Automation of Complex Power Systems, RWTH Aachen University, 52064 Aachen, Germany ]

[ [mirko.ginocchi@eonerc.rwth-aachen.de](mailto:mirko.ginocchi@eonerc.rwth-aachen.de) – <https://www.acs.eonerc.rwth-aachen.de/> ]