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Publication date
2019

Document Version
Final published version

Published in
Smart Grid Co-Simulation by Developing an FMI-Compliant Interface for PSCAD

Citation (APA)
Martinez Carrasco, E., Villén Martínez, M. T., Borroy Vicente, S., López Cortón, D., Popov, M., & Grasset, H. (2019). New faulted phase selector solution for dealing with the effects of Type-4 Wind Turbine on present protection relaying algorithms. In *Smart Grid Co-Simulation by Developing an FMI-Compliant Interface for PSCAD* (2019 ed.). Article 1499 CIRED. https://www.cired-repository.org/handle/20.500.12455/424

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

NEW FAULTED PHASE SELECTOR SOLUTION FOR DEALING WITH THE EFFECTS OF TYPE-4 WIND TURBINE ON PRESENT PROTECTION RELAYING ALGORITHMS

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ABSTRACT

Type 4 wind turbines are becoming one of the most employed technologies for all new wind turbines installed in the power system and their penetration is expected to increase. This technology presents the advantage that of fully decoupling the behavior of the generator from grid disturbances. This decoupling helps the wind turbine to reach the compliance requirements of international grid codes [1] during grid disturbances.

Considering such circumstance, within Work Package 4 of EU funded MIGRATE Project, an ad-hoc Type 4 wind turbine model has been developed in Real-Time Digital Simulator (RTDS) platform, including algorithms for international grid code compliance and independent controls for positive and negative sequence current. The objective of developing such detailed RTDS model is to apply tests in laboratory to real protection relays, from different vendors, to study potential problems or limitations of present protection algorithms in the case of high penetration of this type of renewable energy generation sources into the grid. The in-depth analysis of the results obtained in such tests allows identifying specific weak points of the present protection algorithms in the considered scenarios, thus paving the way for the research on new protective solutions, as it is shown in the present paper.

INTRODUCTION

To analyze potential relays' limitations, mass tests for three different protection functions (distance, line differential and ground directional overcurrent) [1] have been applied in order to compare the behavior of the aforementioned functions in high renewable generation penetration scenarios with the same disturbances in a 100%-synchronous generation-scenario.

This paper shows the conclusions and the results obtained in the tests applied to four different vendors (called in this document A, B, C and D). This paper shows the results obtained for distance protection, which performance was especially problematic under fault current contribution coming from Type-4 Wind Turbine. To solve these issues found in the tests, a new algorithm has been developed and its results are shown in this paper.

BENCHMARK MODEL AND STUDY CASES

For the presented protection behavior study, faults have been applied on the benchmark grid shown in Figure 1. The grid model is implemented in RTDS with the objective of making tests in real time:

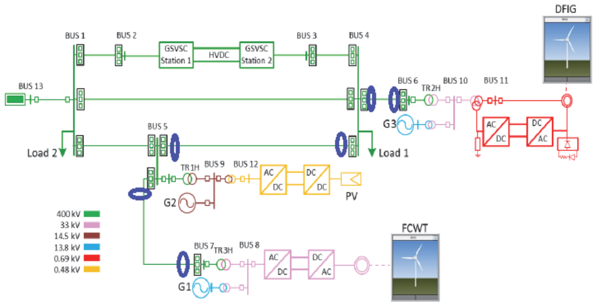

Figure 1. Benchmark model with CTs remarked [2]

As depicted in Figure 1, Type 4 wind turbine is connected at bus 8.

Therefore, line 5-7 is chosen as the protected line for the study shown in this paper. Protection relays at bus 7 side of the line 5-7 see the current contribution either from a synchronous generator (G1) or from the Type-4 Wind Turbine (FCWT). The alternative connection of synchronous and renewable generation provides the comparison of the protection behavior under traditional current contribution from synchronous generation (Figure 2) and type-4 wind turbine (Figure 3).

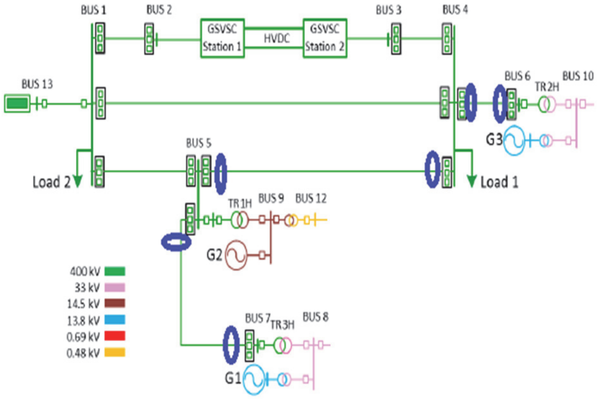

Figure 2. Synchronous generation study line 5-7, bus 7 position. 100% synchronous generation grid

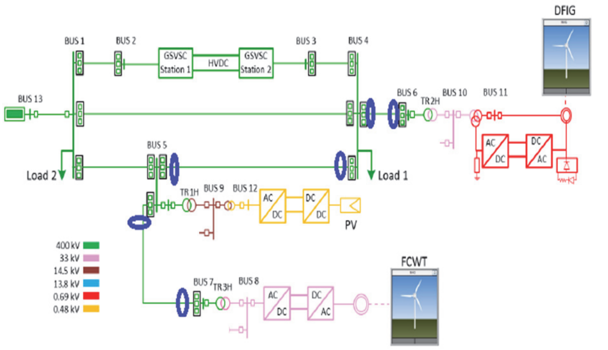

Figure 3. Type-4 Wind turbine generation study line 5-7, bus 7 position. 100% renewable generation grid [1]

Grid configuration shown in Figure 2 is applied to obtain the base case and finally validate the settings used for the three protection functions. Once the protection behavior is validated according to the criteria shown in [1], the base case to compare with is defined and tests with type-4 wind turbine with the same protection settings are performed. The objective of this comparison is to know if present protection algorithms are still valid under the increasing penetration of renewable energies.

Based on the benchmark network and types of generators explained above, the variables involved in the tests were:

- Different fault locations: Faults were applied within zone 1 and zone 2 for distance protection tests, faults inside and outside the protected line were done for line differential protection testing and forward/backward faults were performed for ground directional overcurrent function.
- Different pre-fault generation of synchronous and Type-4 Wind Turbine: 40 MW and 200 MW.
- Different types of fault: Single line to ground (SLG), line to line (LL), line to line to ground (LLG) and three phase faults (LLL).
- Solid faults were applied in the case of distance protection tests to avoid well-known classical problems associated to overreach/underreach actuations of this function with resistive faults.
- Symmetrical current contribution from Type 4 Wind Turbine even in the case of asymmetrical faults.

TESTS APPLIED FOR THE ANALYSIS

Distance protection is the function that has been found as the function most in trouble due to the high penetration of renewables, as explained below in the present section. Line differential and ground directional overcurrent worked properly during the tests, so they are not treated in this paper.

Synchronous generation scenario

As stated before, settings for distance protection are firstly validated with synchronous generation scenario with solid faults. Once the protection relays provide correct tripping times[2] for both zone 1 faults and zone 2 of the distance protection, the settings are considered correct and are the starting point for test with contribution from renewable energies.

Therefore, results obtained for line 5-7 with synchronous generation scenario are:

- Trip times are correct (less than 45 ms) for faults in zone 1 with:
  - Generation level of 40 and 170 MW
  - Type of fault: Single line to ground, line to line, line to line to ground and three-phase to ground
- Trip times are correct (less than 440 ms) for faults in zone 2 with:
  - Generation level of 40 and 170 MW
  - Type of fault: Single line to ground, line to line, line to line to ground and three-phase to ground

Renewable generation scenario

Once the settings are validated for the base case, the 100% renewable generation scenario is tested. Results are presented in this section in terms of statistic results.

Figure 4. Distribution of missed trips between different types of faults for the four different vendors (percentage of missed trips over the total number of faults) for 100% renewables scenario

According to the results observed for these four relays, two main initial conclusions can be drafted:

- Line to line are, in general terms, taking into account global results for all protections, the type of faults that present a worse conditions from the point of view of the protection relay behavior. At this point, it is important to note that Type 4 Wind Turbine [3] [4] is designed and set to inject only positive sequence current once the control has acted during the fault even in the case of asymmetrical faults [5]. The control mode of the generator during asymmetrical faults (negative sequence current equal to zero) is shown as especially problematic for protections when there is not zero sequence current.

- Faults involving ground (single and double phase), in general, present problems for protections but less than the isolated double phase fault. In this case, the zero-sequence current flowing through the neutral of

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[1] Slack bus remains always connected to provide voltage reference to all generator converters

[2] According to the settings defined for the relays under test, following common TSO setting criteria

the transformer is helping the protection to detect the fault.

Based on these results, oscillography have been analyzed to know exactly which internal digital signals are being activated in protection relays during the faults. These digital signals give the information to the user about what is happening inside each protection relay.
According to the results obtained and the control strategy of the Type 4 Wind turbine, the best type of fault to analyze in this case is the phase to phase fault isolated from ground as protections have shown the worst behavior for this type of faults. Figure 5 shows each sequence of the states during a line to line fault. Initially, at the left side of the waveform the current can be observed during the pre-fault state (therefore healthy balance currents). Once the fault is applied, and during the first instants of the fault (8-15 ms), the converter injects both positive and negative sequence currents. When the control reacts to this fault situation, there is a transition state where there is still a mix of positive and negative sequence currents. During this transition period, control acts and reduces the quantity of negative sequence current. This period takes another 20-30 ms. Finally, after two to two and a half electric cycles, the whole current provided by the power converter is only composed by positive sequence current. During the first moments after the fault inception, the power electronics provide a peak of current up to three times the nominal value [6] . These currents are rapidly damped until the steady state of the fault, where current value is limited to around 1.1 pu.

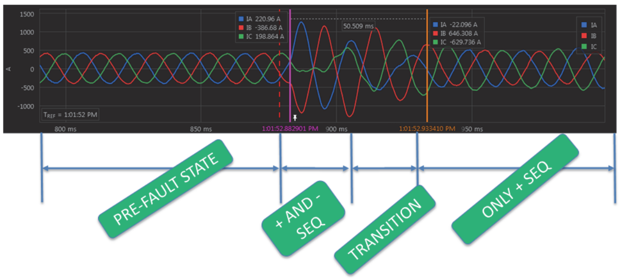


Figure 5. Currents seen by protection relays during a phase to phase fault isolated from ground

Figure 6 shows the current, voltage and digital signals (without their original names in order to preserve the confidentiality regarding vendors' identity) obtained for a line to line fault between phases A and B at 70% of the line with 200 MW generation level coming from the Type 4 Wind Turbine. Here it can be seen that the transition between the initial state of the fault (with both positive and negative sequence at the same time) and its steady state (only with positive sequence current even with asymmetrical faults) can be problematic for distance algorithms in terms of:

- Directionality declaration: Reverse directionality is declared in the transition state (Figure 6). However, fault is forward. Due to this directionality declaration, the forward distance elements cannot be activated and the fault is not cleared in zone 1 times.
- Selection of faulted phase: Initially, the presence of both positive and negative sequence current after the fault inception supports the phase fault selector. However, during the transition period, the fault selector does not operate correctly so that the distance elements cannot be activated to trip the fault within the correct time.
- Impedance measurement is not constant during the transition period, this will lead to a non-predictable behavior either non-tripping or tripping of the fault (providing that the directionality permission and fault phase selector allow the operation of the distance elements). In any case, zone 1 tripping will normally experience delayed operations due to this variable impedance measurement during the transition period.

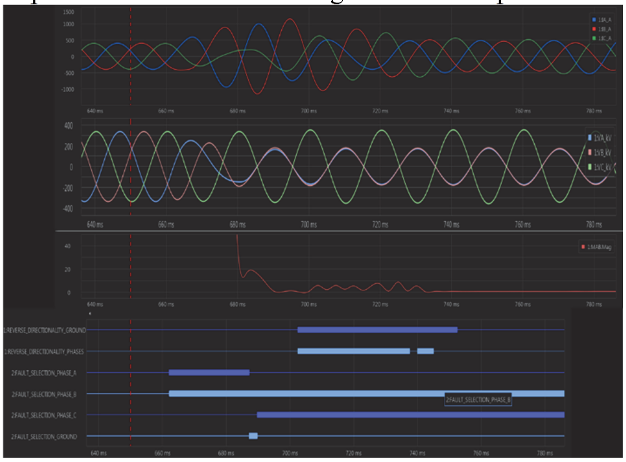


Figure 6. Protection relay oscillography: (From the top to the bottom of the graph) Current, voltage, impedance and digital signals. LL fault and Type 4 Wind Turbine current contribution

CONCLUSIONS OF THE TESTS

During the study carried out by Working Package 4 of MIGRATE Project, several problems have been found for distance protection algorithms with present protection criteria. The highlights of the conclusions obtained are:

- Line to line fault has been found as the most problematic type of fault to be detected for distance protection.
- Ground current, which is present in single line to ground and line to line to ground faults due to the grounding of the transformers, may help the detection of faults.
- The lack of negative sequence current (even during asymmetrical faults) due to the control algorithms implemented on PV generator and Type 4 Wind Turbine has been observed as problematic for distance protection algorithm in terms of:
    - Directionality declaration
    - Faulted phase selection
- Type 4 wind turbines present a clearly different current contribution under fault situation in comparison to traditional synchronous generators and

must be taken into account from the point of view of possible improvement of protection algorithms.

PROPOSAL OF A NEW ALGORITHM AND TESTING

Based on the results and conclusions obtained from the RTDS tests performed to the four different vendors to distance protection, CIRCE has developed a new algorithm to deal with the most problematic points observed for distance protection: directionality declaration and faulted phase selection.

This algorithm, which is in a patent process, improves the identification of the faulted phase and directionality, working in parallel with the impedance measurement of protection relay, helping therefore to potentially improve the behavior of distance protection in a future scenario of high penetration of renewable energies.

It has been designed as a multi-criteria algorithm and it is able to adapt for different time responses of current control of renewable energies and fault contribution after the inception of this fault.

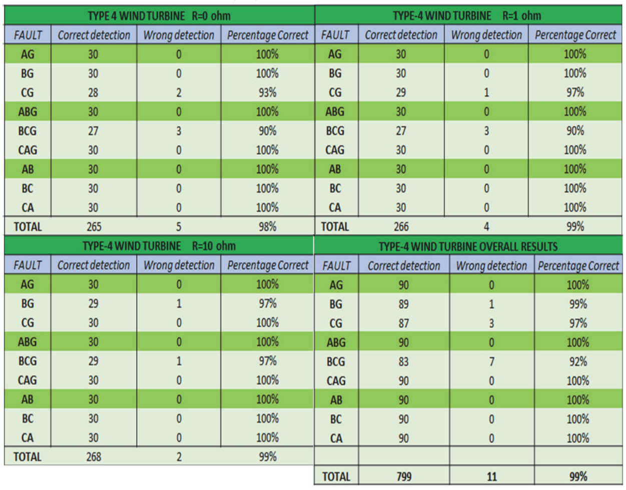
To check the behavior of the developed algorithm, the same philosophy for test cases explained in the section *"tests applied for the analysis"* and additional tests have been performed. New test variables such as different fault resistances and type of faults have been applied with the aim to enrich the study and build a solid algorithm. Accordingly, the following parameters have been changed, using automation script files, for each simulation:

- Scenario: Renewable generation.
- Line under test: Line 57 for Type-4 Wind Turbine tests and line 45 for PV generator tests.
- Distance to the fault: 0%, 50%, 70%, 90%, 100% forward of the line from bus 7 for type 4 wind turbine and from bus 5 for PV generator. Additionally, for backward faults in line 57 the fault is applied behind bus 5 (100% of the line from bus 7) with the protection located at bus 5. In this way, the protection algorithm sees a backward fault with current contribution coming from type 4 wind turbine. (6 combinations for line 57 and 5 for line 45)
- Generation level: 40 and 200 MW. (two combinations)
- Type of faults: AG, BG, CG, AB, BC, CA, ABG, BCG, CAG. (nine combinations)
- Fault resistance: 0, 1 and 10 ohm. (three combinations)
- Repetitiveness: Three times each fault. (three combinations)

The overall number of combinations rise up until 270 faults per line and per value of fault resistance. Tables of results depicted in Table 1 and Table 2 per different fault resistances and sorted by type of fault, show the summary of the results of 30 faults per row due to the combinations of two generation levels (40/200 MW), 5 types of faults (0, 50, 70, 90 and 100%) with a repetitiveness of three times each fault to check the consistency of the results.

In comparison with missed trips observed in Figure 4 (for present protection algorithms), mostly due to the problems with faulted phase selection and directionality declaration, with the new solution proposed, according to the tests performed, faulted phase selection has been solved for Type-4 Wind Turbine (line 57) and PV generator (line 45) current contribution, as it is shown in the following tables. It can be noted in Table 1 and Table 2 that 100% of AG, ABG and AB faults (highlighted in dark green) were correctly detected by the new faulted phase selector algorithm.

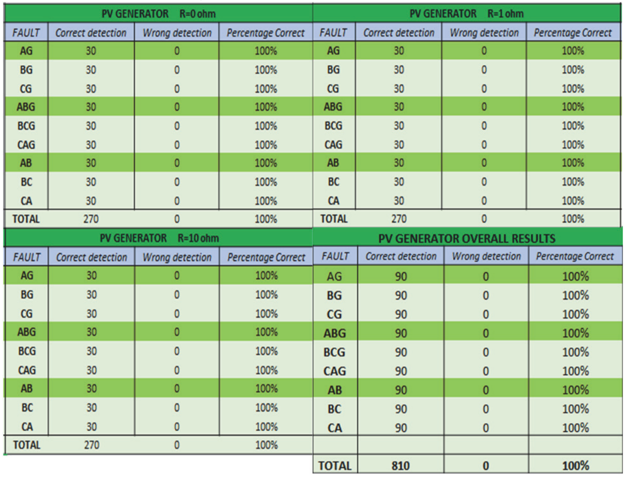
Table 1. Results obtained for type 4 wind turbine (line 57). Fault resistance 0, 1, 10 ohm and overall results



TYPE 4 WIND TURBINE R=0 ohm				TYPE-4 WIND TURBINE R=1 ohm			
FAULT	*Correct detection*	*Wrong detection*	*Percentage Correct*	*FAULT*	*Correct detection*	*Wrong detection*	*Percentage Correct*
AG	30	0	100%	AG	30	0	100%
BG	30	0	100%	BG	30	0	100%
CG	28	2	93%	CG	29	1	97%
ABG	30	0	100%	ABG	30	0	100%
BCG	27	3	90%	BCG	27	3	90%
CAG	30	0	100%	CAG	30	0	100%
AB	30	0	100%	AB	30	0	100%
BC	30	0	100%	BC	30	0	100%
CA	30	0	100%	CA	30	0	100%
TOTAL	265	5	98%	TOTAL	266	4	99%

TYPE-4 WIND TURBINE R=10 ohm				TYPE-4 WIND TURBINE OVERALL RESULTS			
FAULT	*Correct detection*	*Wrong detection*	*Percentage Correct*	*FAULT*	*Correct detection*	*Wrong detection*	*Percentage Correct*
AG	30	0	100%	AG	90	0	100%
BG	29	1	97%	BG	89	1	99%
CG	30	0	100%	CG	87	3	97%
ABG	30	0	100%	ABG	90	0	100%
BCG	29	1	97%	BCG	83	7	92%
CAG	30	0	100%	CAG	90	0	100%
AB	30	0	100%	AB	90	0	100%
BC	30	0	100%	BC	90	0	100%
CA	30	0	100%	CA	90	0	100%
TOTAL	268	2	99%				
				TOTAL	799	11	99%

Table 2. Results obtained for PV generator (line 45). Fault resistance 0, 1, 10 ohm and overall results



PV GENERATOR R=0 ohm				PV GENERATOR R=1 ohm			
FAULT	*Correct detection*	*Wrong detection*	*Percentage Correct*	*FAULT*	*Correct detection*	*Wrong detection*	*Percentage Correct*
AG	30	0	100%	AG	30	0	100%
BG	30	0	100%	BG	30	0	100%
CG	30	0	100%	CG	30	0	100%
ABG	30	0	100%	ABG	30	0	100%
BCG	30	0	100%	BCG	30	0	100%
CAG	30	0	100%	CAG	30	0	100%
AB	30	0	100%	AB	30	0	100%
BC	30	0	100%	BC	30	0	100%
CA	30	0	100%	CA	30	0	100%
TOTAL	270	0	100%	TOTAL	270	0	100%

PV GENERATOR R=10 ohm				PV GENERATOR OVERALL RESULTS			
FAULT	*Correct detection*	*Wrong detection*	*Percentage Correct*	*FAULT*	*Correct detection*	*Wrong detection*	*Percentage Correct*
AG	30	0	100%	AG	90	0	100%
BG	30	0	100%	BG	90	0	100%
CG	30	0	100%	CG	90	0	100%
ABG	30	0	100%	ABG	90	0	100%
BCG	30	0	100%	BCG	90	0	100%
CAG	30	0	100%	CAG	90	0	100%
AB	30	0	100%	AB	90	0	100%
BC	30	0	100%	BC	90	0	100%
CA	30	0	100%	CA	90	0	100%
TOTAL	270	0	100%				
				TOTAL	810	0	100%

OSCILLOGRAPHY OBTAINED FROM TYPE-4 WIND TURBINE

Figure 7 shows an example of a line to line fault applied at 70% of the line 57 (measured from bus 7), with 100% fault current contribution coming from a type-4 Wind Turbine Generation providing 200 MW at the moment of the fault inception. It can be observed as line to line, AB fault has been correctly identified: both faulted phases AB and forward directionality. This algorithm, that solves the issues found for distance protection in present algorithms regarding to faulted phase selection and directionality, working in parallel with impedance measurement loops of present protection relays will be able to correctly trip the fault.

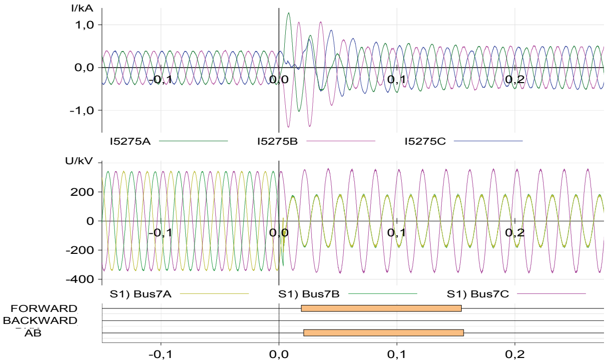


Figure 7. Oscillography obtained for a Line to Line fault (AB)

NEXT FUTURE AMBITION

During 2019, MIGRATE Project is still in process. This last stage of the project aims to perform a *Proof of Concepts* by means of programming the developed algorithm in a physical protection device via firmware update of a Schneider Electric MiCOM P545 device. With this firmware update, the faulted phase selector and directionality algorithm will work in parallel with the impedance loop measurements already present in the distance relay. Once this new firmware is updated, tests performed to the faulted phase selection and directionality algorithm will provide an even more accurate comparison between the behavior of present protection relays shown in section *"tests applied for the analysis"* and the performance with the proposed algorithm implemented in a real device. Besides, this implementation in a real protection relay aims to demonstrate the capability of the developed algorithm to run in a commercial device and, therefore, its applicability for the industry.

Nevertheless, considering that the main problem for missed trips was the wrong action of faulted phase selection and directionality due to the current contribution from renewables (results summarized in Figure 4 for SLG faults (AG), line to line faults (AB) and line-to-line-to-ground faults (ABG)), the results that Table 1 and Table 2 shows for the developed algorithm regarding to these type of faults are really encouraging.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691800.

DISCLAIMER

This paper reflects the MIGRATE consortium view and the European Commission is not responsible for any use that may be made of the information it contains.

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