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Enhancing Distance Protection Performance in Transmission Systems with Renewable Energy Utilization

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***Abstract*— This paper deals with a comprehensive analysis to test the performance of available distance protection, that can be used in transmission networks with high penetration of converter-based distribution generation. For this, a new benchmark model has been developed according to the European Network of Transmission System Operators (ENTSO-e) guidelines. A 400 kV transmission network has been modeled in detail by taking into account wind turbine (WT) Type-3, Type-4 and PV generation as well as conventional generation where applicable. The network also makes use of a point-to-point HVDC connection, and it can be used to simulate variable penetration of distribution generation up to 100%. The system is modeled in details by making use of EMT models developed in RTDS environment. Numerous tests have been performed for protective relays from different vendors and different grid code constraints. The performance of the different vendor distance relay is analyzed for different fault types on transmission line. Further, a transient-based hybrid scheme has been discussed that is capable of operating under challenging conditions. The work is realized in the frame of the large EU Horizon 2020 project MIGRATE to study the performance of power system protection with large penetration of power electronic devices.**

Keywords*— *Protection, future power systems, real time testing, modeling, protection schemes, Migrate.

I. INTRODUCTION

Participants at the Paris Climate Change Conference in 2015 agreed to decrease the level of CO_2 significantly by 2050. In the electricity sector, this is interpreted as a need for high penetration of renewable energy. Therefore, a large number of coal and nuclear power plants are planned to be decommissioned and replaced by renewable energy sources (RES) in the near future. Low system inertia, bi-directional fault currents and different composition of energy production and loads make the operation, control and protection of such systems quite complicated. Technical requirements regarding interconnection of distribution generation (DG) in the system and issues like islanding, abnormal conditions, power quality that DGs need to fulfill are reported in [1]. The interconnection of power electronic (PE) based generators should be in line with the fault ride through capabilities imposed by ENTSOE [2], and also with the grid codes applied in different European countries [3], as well as their respective counterparts around the world, such as that of the Federal Energy Regulatory Commission (FERC) in North America. For testing protection coordination, these requirements must be taken into account, prior to checking the robustness of a protection function under different fault conditions. In order to do this, firstly a suitable test system should be built, which is capable of simulating system real time conditions for different levels of RES. The IEEE Power System Relaying Committee has already proposed a benchmark that can be used to test protection devices. However, it is only applicable for testing a conventional system since the requirements for PE-based sources. Studies of protection performances in converter-based power systems with DGs, show that there are many cases of nuisance tripping of the protection when Photovoltaic plant (PV), Type-3 and Type-4 wind turbines (WTs) are used [3,4].

Present protection practices have been essentially developed for systems where synchronous generators (SG) are dominant. In the future, however, part of the traditional concepts and philosophies may need adaptation in order to cope with large penetrations of RES. Factors such as the amplitude and the angle of currents injected, or the speed of response, which is mainly related to converter control algorithms, may influence traditional protection schemes. In this paper, test results of the efficiency of commercial distance relays of different vendors are presented by studying the system performance in real time. For this purpose, a refined test system has been built that takes into account complete aggregated electromagnetic transient (EMT) models for Type-3 and Type-4 WTs as well as PV. This system can be used for different levels of RES penetration in correlation with conventional generation. In

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this context:

- The behavior of commercial distance relays for different line faults is studied under high penetration of RES.
- Some results are presented with an improved algorithm in real time capable to decrease the number of maloperations.

II. GRID CODE REQUIREMENTS FOLLOWING FAULTS

During a short-circuit fault, the PE-interfaced sources should meet the requirements enforced by the grid codes. For this work, Type-3, Type-4 WTs and the PV sources are equipped with control mechanisms enabling them to follow the TenneT grid code [5].

The voltage source converter (VSC) that interconnects the RES to the AC grid should remain connected to the grid during faults, according to the Low Voltage Ride Through (LVRT) profile. The grid codes define the increment of reactive current to be injected by the RES as a function of the positive sequence voltage dip measured at the VSC terminal.

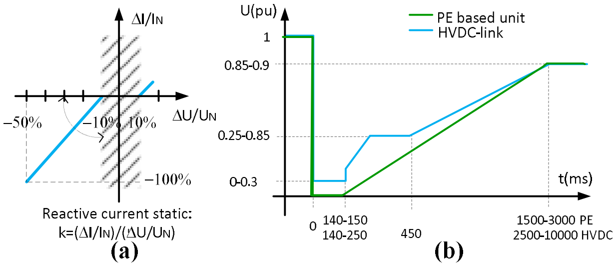


Fig. 1. TenneT grid code: a) Dynamic current requirements and b) Low voltage ride through

The specified details and the LVRT profiles used in this work for the PE generating units and HVDC–link are depicted in Fig.1a. In addition, the reactive power supply is a requirement during the voltage dips. The corresponding voltage control characteristic is shown in Fig.1b. The control systems used for the HVDC and PE generator units calculate the increment of reactive current, according to the voltage drop based on the grid code.

III. TEST NETWORK AND TESTING PROCEDURES

A. Description of the test network

The test network applied to study different scenarios involves a point-to-point HVDC link, two wind farms type-3 and type-4, a photovoltaic plant and conventional generation in parallel with all the PEs to easily change from a system with SGs to a system with high penetration of PE-based generators. The test system is developed in RSCAD that works in Real Time Digital Simulator (RTDS) environment and it is shown in Fig.2. This test system is connected on one side to an infinite grid. Even though the HVDC link is not studied in this project, it can be used in the future for different purposes. The crucial components that require particular attention and modeling efforts are:

- Doubly Fed Induction Generator (DFIG).
- Full converter Permanent Magnet Synchronous Generator (PMSG).
- Two level VSC converter for the HVDC lines.
- PV model connected to the system through a full converter.

The PV model includes the Solar Panel model, the DC bus, the power inverter and a Maximum Power Point Tracking (MPPT) algorithm. The model contains a DC/DC and a DC/AC converter. On the other hand, the model of the DFIG system includes a chopper and a crowbar protection elements. A PMSG is also developed in detail in per unit value so that the output power is scaled to the corresponding penetrating power level. In order to respond properly to the asymmetrical fault currents, negative sequence control has also been taken into account for all DGs. In this way, it is possible to simulate all fault types with a response of the PE close to the reality. CTs and VTs are taken as ideal as the goal is to see the actual performance of the relays. Their ratios are, 2 kA/5 A and 440 kV/110 V. The results of the simulations are verified by some measurements and other simulations as reported in [6,7]. The point-to-point HVDC connection has been developed according to [8] and it also takes into account positive and negative sequence control.

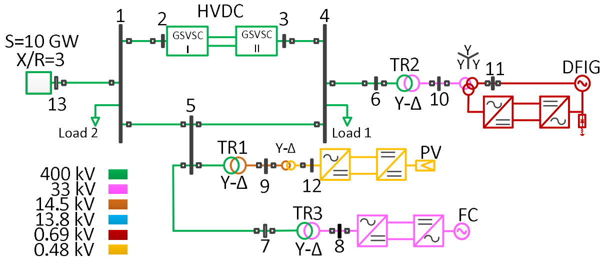


Fig. 2. Test network for studying protection performance.

The behavior of four distance protective relays from different manufacturers has been assessed under different penetration levels of RES. The distance relays and their associated current and voltage transformers are located at bus-6 (for line 4-6), bus-5 (for line 4-5) and bus-7 (for line 5-7). Bus 13 is the grid equivalent that represents the slack bus. As a reference for all the converters, it will remain always connected during tests. This grid equivalent provides the voltage reference for the RES models (Type-3 and Type-4 wind turbines and PV generator). As shown in Fig.2, the lines chosen to evaluate the behavior of protective relays are:

- **Line 5-7:** the behavior of protection functions will be assessed based on the Type-4 wind turbine contribution. The model used will include all the lines connected, as shown in Fig.2. The "Grid side" bus is bus 5 while "DG side" is bus 7.
- **Line 4-5:** the behavior of protection functions will be assessed based on the PV generator contribution. The only current contribution seen by protection located at bus 5 during faults will be provided from line 5-7. The "Grid side" bus is bus 4 while "DG side" is bus 5.
- **Line 4-6:** the behavior of protection functions will be assessed based on the Type-3 wind turbine operation. For the studies on this line, line 1-4 will be disconnected. The "Grid side" bus is bus 4 while "DG side" is bus 6.

The values of the distance relay settings are the same for all relays and defined according to ENTSOE setting criteria. The test parameters used for the validation of distance protection are according to IEC 62055-121:2014 standard for protection testing, which are valid for radial configurations with current supplied from only one side and no contribution from the other side.

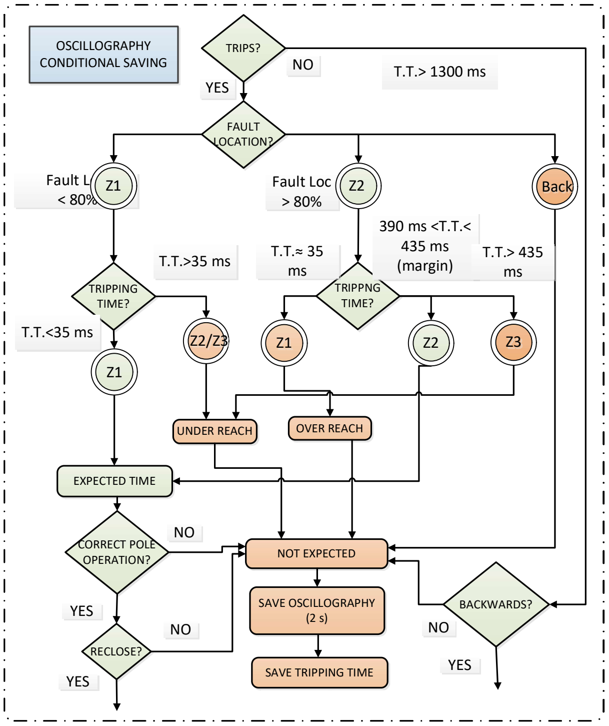


Fig.3. Flow chart of the distance protection function script in RTDS.

For the distance protection: faults within zone 1 must be tripped in less than 45 ms. The conditions for these tests are listed below:

- Generation level from the PE generator: 40 MW or 200 MW in order to simulate low and high power infeed.
- The fault location varying from 0% to 80% within zone-1. The test of each location is repeated three times to ensure that the captured behaviour is correct.
- Type of fault: line-to-ground (LG), line-to-line (LL), line-to-line- to-ground (LLG) and three-phase (LLL).
- Fault resistance: For all the tests bolted faults have been applied, since the effect of secondary arcing was beyond the scope of this work. In this way, the focus was to analyse the effect of different RES fault current levels on distance protection.

Once the settings have been validated for the base-case (with only synchronous generators in the system), the RES scenario were tested. The flowchart of the distance relay function script to perform automatic testing in RTDS is depicted in Fig.3. Based on this script, the oscillography of each relay was recorded during suspicious maloperation and the trip times are recorded and classified into trip, delayed trip or no trip per relay.

IV. HARDWARE-IN-LOOP TESTING OF EXISTING DISTANCE RELAY: RESULT AND ANALYSIS

By applying HiL, the DFIG impact on the performance of the distance relays for line 4-6 was observed. The complexity of DFIG-based transmission systems makes distance protection challenging. For the testing of distance relay performance for fault currents generated by the RES, all SGs are disconnected from the system.

A. Line 4-6: available distance relay performance

In this section, the obtained results are presented in terms of statistical figures. Faults are applied for both 40MW and 200MW active power injections from the RES. The obtained results for all types of faults at different locations on the observed line and generation levels were recorded. A total of 4608 test cases were simulated and the obtained results are summarized. The different test cases are listed in Table I.

TABLE I
TEST CASES

Scenario	Distance	Type
Grid	2	Strong, Weak
Generator level	2	40MW, 200MW
Scenario	3	SG, RWG, MIX
Point of line	8	Back, 0,50,70,80,90,100, 100 out (%line)
Type of fault	4	LN, LLN, LL, and LLL
Impedance	4	0Ω, 1Ω, 10Ω, 75Ω
Repetitions	3	
Total	4608	

According to the obtained results for line 4-6, it can be seen relay A performs better than relays B, C and D. This difference results essentially from different algorithms implemented inside each product. According to this comparison for both strong and weak grid conditions, the next study compares the relay performances based on different fault types. Fig. 4 shows the results related to missed trips for the four relays.

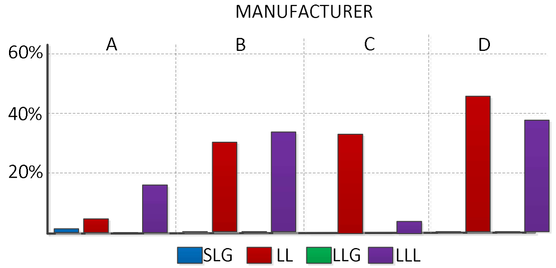


Fig.4. Testing performance of relays of four different vendors (missed trips).

In this analysis, different behaviours can be observed for different relays. It should be pointed out that the voltage and current signals of the protective relays are the same for all relays. Relay A and Relay B experience more difficulties for LLL and LL faults. LLG fault is the least problematic fault and LG fault is not problematic for any condition. It is very interesting that detecting faults involving ground was not a problem at all for relay C. This is a clear difference than that of other three vendors. Relay D is similar to protective relay B; it performs poorly during LL and LLL faults whilst faults involving ground do not prevent the relay from generating a correct a trip command. However, Fig. 5 reveals that there is a high percentage of delayed trips using all the relays. The differences are due to the algorithms used in each relay, which for the authors are not known. The threshold is defined by the TSO and the protection function is the same for all the relays.

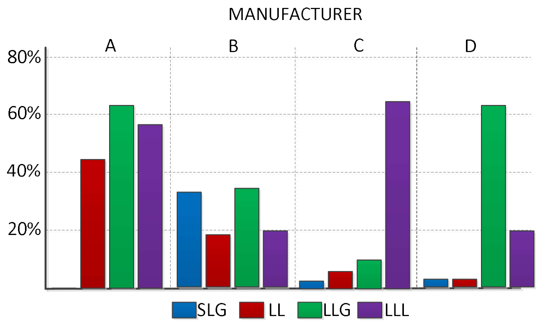


Fig.5. Delayed trips per type of fault and relay brand in percentage.

Delayed trips are also marked as relay maloperation. Relay A trips with a delay for more than 40% of the LL, LLG and LLL faults. Relay B presents low percentages of delayed trips. For relay C, more than 60% of the delayed trips occur during LLL faults and relay D experiences high percentage of delays during LLG faults. It is worth mentioning that the best performance for all the relays is during single-line-to-ground faults (LG) and ungrounded faults, LL and LLL faults are a point of attention for all relays.

B. Fault detection challenges

From the test results, it has been observed that faults involving ground are not problematic for the studied distance relays as depicted in Fig.6.

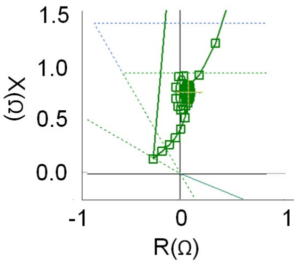
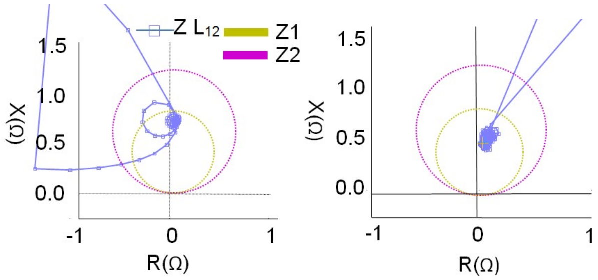


Fig.6. Manufacturers distance relay performance for phase-to-ground fault with 40 MW generation level with protection zones.



(a) (b)

Fig.7. Manufacturers distance relay performance for phase-to-phase fault with generation level (a) 200 MW Trip condition and, (b) 40 MW No-Trip Condition.

For ungrounded faults during low power generation level (i.e. 40 MW), none of the relays trip, as depicted in Fig.7(b). However, they perform well for the same fault in case of a high power infeed (i.e. 200MW) as depicted in Fig.7(a). It can be seen that the impedance enters gradually (in case of relay tripping) or abruptly (in case of relay failure) into zone 1 of each relay. The fact that in some cases, the protection fails to operate results from the relay failure to detect the fault. In order to overcome this shortcoming of the commercial distance relays, a wavelet based transient hybrid fault detection algorithm has been developed and tested in an HiL setup.

V. PROPOSED FAULT DETECTION ALGORITHM

As depicted in Table-II, testing the relay performance shows that none of the distance relays is able to detect ungrounded faults in systems with low DFIG levels (i.e. below or equal to 40 MW). Therefore, to improve the performance of the fault detection element in commercial distance relays, a viable solution is to make use of a transient based hybrid algorithm [9]. Such an algorithm should activate the relay only during ungrounded faults with a low generation level. The other types of line faults will be easily handled by the internal algorithms of commercial distance relays. For these types of faults, the proposed transient algorithm is not in an active mode based on the implemented logic. The flow chart of the hybrid scheme proposed for the improvement of the ability of distance relays for ungrounded fault detection is shown in Fig. 8.

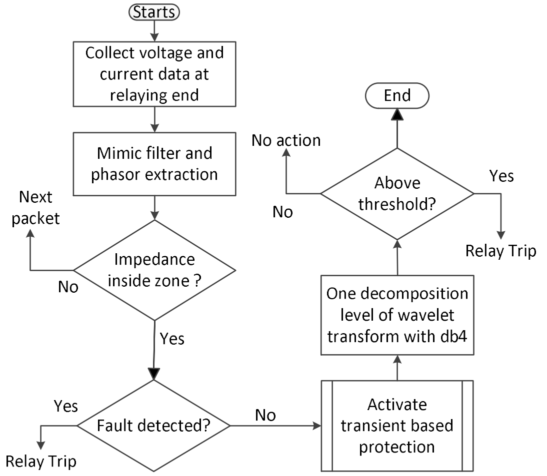


Fig.8. Hybrid scheme for improvement of distance relay fault detection element.

A. Performance of transient based fault detection a scheme

The first decomposition of the wavelet, which corresponds to the D1 level component, is sufficient to detect the fault condition. Therefore, the computational cost of the proposed method is very low and easy to implement in real-time. The proposed fault detection method is able to detect faults within half a cycle following the fault inception when the fault occurs in zone-1. For faults occurring in zone-2 of the relay, an intentional delay associated with zone-2 is added to the response time of the proposed method. Those cases in which the protection failed to detect the fault are again tested with the proposed hybrid scheme. The obtained results are depicted in Fig. 9 and Fig.10.

The cases representing failures are Case-1: Phase-to-phase fault with 40MW generation supply, and Case-2: LLL fault with 40MW generation supply. Table II shows the results obtained with the proposed algorithm for different operating conditions. It can be seen that the response time of the fault detection process is not affected by varying operating condition. The threshold chosen, 0.1pu, is immune to 30 dB noise while making it possible to detect the high impedance faults successfully. The trip command for the first zone is instantaneous whilst the second zone trips are intentionally delayed by 400ms.

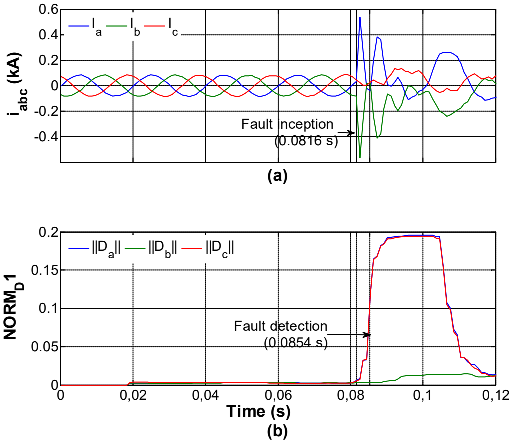


Fig.9. Case-1 :Phase-to-phase fault with 40MW generation level (a) Two-phase fault current left; (c) norm D1-component used for fault detection

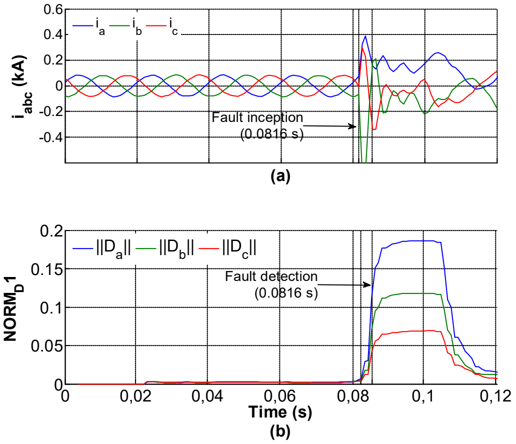


Fig.10. Case-2: LLL fault with 40MW generation level; (a) LLL fault current left (c) norm D1- component used for fault detection.

TABLE II

TESTING PERFORMANCE

Characteristics				**Existing Method**		**Proposed Method**	
Test	Faults Type	Fault Zone	Generation Level (MW)	Trip Decision	Trip Time (*ms*)	Trip Decision	Trip Time (*ms*)
1	LG	1	200	Trip	<45	Trip	<20
2	LG	1	40	Trip	<45	Trip	<20
3	LLG	1	200	Trip	<45	Trip	<20
4	LLG	1	40	Trip	<45	Trip	<20
5	LL	1	200	Trip	<45	Trip	<20
6	LL	1	40	No trip	-	Trip	<20
7	LLL	1	200	Trip	<45	Trip	<20
8	LLL	1	40	No trip	-	Trip	<20
9	LG	2	200	Trip	<440	Trip	<415
10	LG	2	40	Trip	<440	Trip	<415
11	LLG	2	200	Trip	<440	Trip	<415
12	LLG	2	40	Trip	<440	Trip	<415
13	LL	2	200	Trip	<440	Trip	<415
14	LL	2	40	No trip	-	Trip	<415
15	LLL	2	200	Trip	<440	Trip	<415
16	LLL	2	40	No trip	-	Trip	<415

VI. CONCLUSIONS

In power systems with high penetration of RES, present distance relays will face difficulties in clearing ungrounded fault currents. Distance relays of different manufacturers may demonstrate different behavior for each type of fault. LL and LLL faults are the most problematic types of faults to detect. After performing a large number of tests, it has been concluded that the starting function of the relay may fail. The correct operation of the starting element of a relay is crucially important for fault detection. It has also been shown that even with minimum starting current setting, the relay fails to detect ungrounded faults for specific cases. This current is not allowed to be set so low in order to maintain security of the protection system. In addition, the relays of some manufacturers experience difficulties not only with the starting current but also with faulty phase selection, which will further delay the relay's decision. In order to improve the performance of fault detection for distance relays, a transient-based hybrid scheme has been developed. The proposed method is mainly aimed at the detection of LL faults, as other fault types are successfully detected by the existing fault detection techniques. Fault resistance in all conducted simulations is assumed to be zero as the analysis is focused only on the effect of RES. The proposed fault detection method is able to detect faults within a half cycle from the fault inception for faults occurring in zone-1. For ungrounded faults occurring in zone-2, the intentional time delay of zone-2 is added to the response time of proposed method. The selection of a suitable threshold is important for accurate fault detection. This is to guarantee security of the protection system against load switching, harmonics which may exist in the system and other uncertainties. Practically speaking, the threshold is better to be set in accordance with the norm of the wavelet transform from a filtered current.

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