PHASOR-BASED AND TIME-DOMAIN TRANSMISSION LINE PROTECTION CONSIDERING WIND POWER INTEGRATION

Jônatas S Costa[1], Rodrigo T Toledo[1], Letícia A Gama[1], Tiago R Honorato[1], Felipe V Lopes[1], Paulo S Pereira Jr[2], Gustavo S Salge[2], Moisés J B B Davi[2]*

[1]*Department of Electrical Engineering, University of Brasília, Brasília, Brazil*
[2]*CONPROVE, Industry and Commerce, Uberlândia, Brazil*
**jonatascosta@lapse.unb.br*

Keywords: PHASOR-BASED PROTECTION, TIME-DOMAIN PROTECTION, TRANSMISSION LINE, WIND GENERATION, PS SIMUL.

Abstract

The increasing integration of converter-interfaced wind power plants into the existing power systems has been a challenge for protection and monitoring functions. As a result, studies on protection performance considering this type of generation have been a topic of great interest to the industry. In this way, this paper evaluates the performance of phasor-based and time-domain protection functions available in real micro-processed protective devices when applied to a 500 kV/60 Hz transmission line that interconnects a wind power generation plant to a traditional power system. The test system was modelled and simulated by means of the Power System Simulator (PS Simul) software, through which different fault scenarios were evaluated by varying parameters such as fault location, fault resistance and inception angle. The obtained results highlight differences in evaluated protective relays' performances when applied to both line terminals, revealing the impact of converter-interfaced wind power plants on the relays' reliability and operation times.

1 Introduction

The spread in demand for renewable energy resources and recent technological developments have intensified the growth of wind power generation. In some countries, wind energy already accounts for a considerable part of the generated electric power [1]. As wind energy sources deployment grows, several challenges arise from their interconnection to the system. These issues are mainly related to power systems dynamics and transient characteristics, which are consequence of aspects such as the variability of energy production and the use of power electronic converters. Thereby, there is a concern with the power system protection operation when wind power integration takes place.

Some studies evaluating short circuit current contributions of electronic-coupled generators into transmission networks during different fault events have demonstrated a different behaviour of wind power plants in comparison to current contributions verified when conventional synchronous generators are taken into account [2]. Such behaviour depends on the wind turbine topology and its associated control scheme, so that it may have a significant impact on the performance of protection relays. Therefore, it is necessary to improve the understanding on how conventional and other emerging protection functions would behave when the integration of different energy sources is considered.

In the context of protection schemes applied to transmission lines that interconnect wind power plants to existing traditional power grids, conventional phasor-based protection solutions have been investigated [3]. Nonetheless, in the authors' best knowledge, comprehensive studies including the performance analysis of phasor-based and time-domain protective relays in the presence of wind farms are still scarce. Indeed, time-domain relays overcome the need for phasor estimation, being based on concepts that seem to be advantageous for systems with weak sources [6], which is an inherent feature of converter-interfaced renewable sources. Thus, this paper evaluates the performance of transmission line real phasor-based and time-domain protective relays, considering a transmission network that interconnects a conventional power system (with traditional generation plants) to a converter-interfaced wind power plant.

To perform the proposed studies, a test system with topology in accordance to a real Brazilian network is modelled and simulated by means of an Electromagnetic Transients Program (EMTP), namely PS Simul [7]. The system consists of a 500 kV/60 Hz transmission line, which connects converter-interfaced wind power units to a power network fed by conventional generation sources. The wind turbines are modelled in detail with the aim to properly represent the influence of converters on the system response during faults, making it possible to analyse a wide variety of realistic scenarios considering different fault features such as resistance, location and inception angle. Finally, massive closed-loop and playback tests are carried out using different transmission line protective relays, from which distance and differential protection elements are evaluated, allowing the assessment of the performance of each technology under the studied fault scenarios.

From the obtained results, the differences between short-circuit contributions from the wind farm and conventional power network is discussed. Then, a comparison between the phasor-based and time-domain protection elements at each line terminal is presented. The results reveal that the presence of wind power plants can indeed affect the relays' performance, influencing not only the protection reliability, but also its operation times.

2 Wind Generation Characteristics

Different technical and operational characteristics of wind generation when compared to traditional synchronous machine-based sources are often reported in the literature [1]. These differences are usually related to the lack of inertia, intermittent generation and circuit topology used for integration to the power network, which can be based on power electronic converters or not.

Regarding converter interfaced-based wind generators, several impacts have been reported in the literature, such as those on fault transients and on protection scheme performance [1],[3]. These include very low and limited short-circuit current contributions, unconventional behaviours of fundamental components of voltages and currents waveforms and insertion of harmonic content [1]. Therefore, the scientific community and industry have made efforts to better understand the effects of these characteristics on the performance of monitoring and protection devices, boosting several researches focused on testing procedures of existing technologies towards identifying advantages, limitations, and possible improvements. Hence, in this paper, a wind power plant composed by several full converter-based wind turbine generator (WTG) units is considered, also called Type 4, whose main features are related to the power electronic converters and controls.

To better illustrate the analysed configuration, Fig. 1 depicts the WTG topology. The turbines play the role of generating mechanical energy, which is converted into electric energy. The modelled wind turbine considers a synchronous generator (SG) which is interfaced to the network by power converters. As a result, the machine is totally uncoupled from the network, allowing its operation over a range of speeds. With regard to power electronic converters, the SG side converter is characterized by a diode rectifier unit and serial boost converter, whereas the grid side converter consists of insulated gate bipolar transistor (IGBT)-based pulse width modulation (PWM).

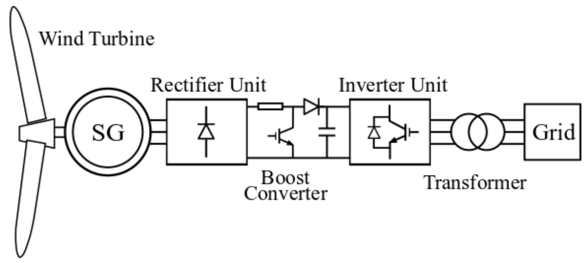

Fig. 1 WTG topology evaluated

3 Fundamentals of Protection Functions

With the advent of micro-processed relays, several protection functions have been embedded into monitoring devices, allowing the application of multi-functional schemes that guarantee proper transmission line protection. In this paper, due to space limitations, the influence of converter-interfaced WTGs is evaluated only from the point of view of distance and differential protection elements, which are widely used as main protection of transmission lines.

Most existing distance and differential relays operate based on phasor-based principles. Nevertheless, as time-domain relays have gained importance in the market, such elements are also studied here. Hence, the main principles of both technologies are briefly described next.

3.1 Distance protection functions

In this paper, for the sake of simplification, phasor-based and time-domain distance protection elements will be referred to as PH21 and TD21 elements, respectively. Based on fault loop phasor quantities, PH21 elements estimate the apparent impedance from the measurement point until the fault, which is in turn evaluated on an R-X diagram. Thus, the Cartesian R-X impedance position is compared with an operation characteristic, making it possible to distinguish faults that take place within a given protected zone (in-zone faults) from out-of-zone events. Fig. 2 illustrates typical mho and quadrilateral operation characteristics, illustrating the impedance trajectory from the pre-fault until the fault period.

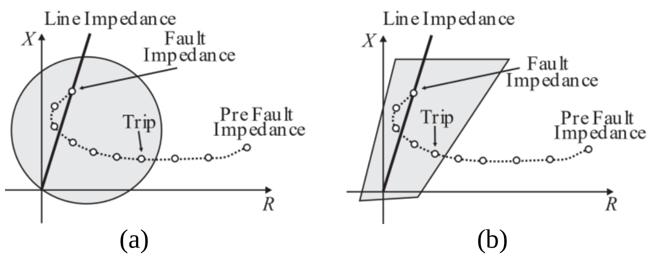

Fig. 2 PH21 element operation principle, considering: (a) mho characteristic; (b) quadrilateral characteristic

Typically, the position of impedances measured by PH21 elements on the R-X diagram is evaluated by means of magnitude or phase angle comparators, which are used to identify the moment at which estimated apparent impedances fall into the operation region [8]. Besides, different strategies are commonly used to improve distance protection security and reliability, such as voltage memory, polarisation strategies, and so on. A diversity of algorithms has been utilized for this end, so that they are not detailed in this paper due to space limitations. Further details on these topics can be found in the protection area literature, such as in [8].

Unlike the PH21 element, the TD21 protection function replaces the apparent impedance analysis by the line voltage profile evaluation [6], overcoming the need for phasor estimation, what speeds up the protection operation.

The TD21 element calculates a restraining voltage V_{RT}, as the voltage at the reaching point, and also estimates an operating voltage V_{OP}, which is taken as the incremental version of the voltage at the reaching point. As a result, as the voltage at the fault point approximates zero in cases of solid short-circuits, incremental quantities tends to be the negative of the pre-fault voltage at the fault location, decreasing its value as the measurement point gets away from the fault or in cases of higher fault resistances. Thus, as illustrated in Fig. 3, if $|V_{OP}| \geq |V_{RT}|$ is verified, an in-zone fault is detected and, otherwise, an out-of-zone is characterized. In Fig. 3, restraining and operating profiles are depicted, where V_{RT} is assumed to be the same over the whole line, being V_{OP1} and V_{OP2} the operating voltages obtained for the out-of-zone fault F1 and for the in-zone fault F2.

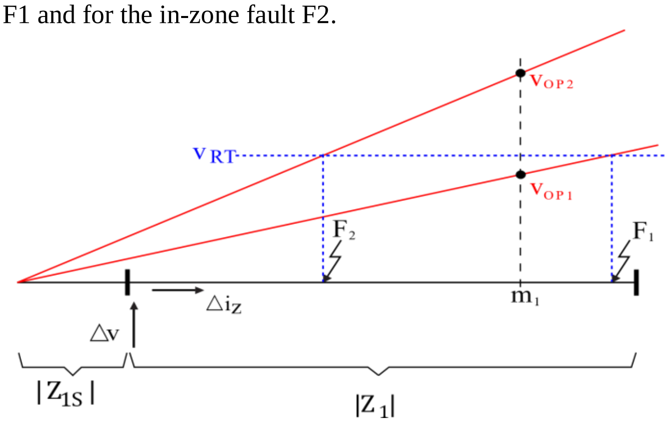

Fig 3. Incremental quantity time-domain-based distance protection operation principle.

Due to security reasons, additional security layers are used in the TD21 element tripping logic, such as overcurrent supervision, phase selection procedures and also directional element supervision [6]. As a result, in-zone faults can be detected by the TD21 element, but the trip command is issued only if time-domain directional elements see a forward fault. Such a feature is important to understand the results presented in the next sections, especially those in which V_{OP} and V_{RT} met the in-zone fault condition, but the TD21 restrained due to its security directional element supervision.

3.2 Differential protection functions

The differential element implements a type of unit protection which has been increasingly applied in transmission networks. As shown in Fig. 4, in its phasor-based version, called here PH87, it compares currents measured from both line terminals, and typically calculates operating and restraining quantities which analysed for the sake of distinguishing line internal from external faults [8]. On the other hand, as shown in Fig. 5, in its time-domain version evaluated in this paper, the differential element analyses traveling waves launched by faults on the line, being called TW87. Such an element compares propagation times, polarities and amplitudes of fault-induced waves detected at both line terminals, also calculating operating and restraining quantities which are evaluated in conjunction of other security layers, such as overcurrent supervision [6].

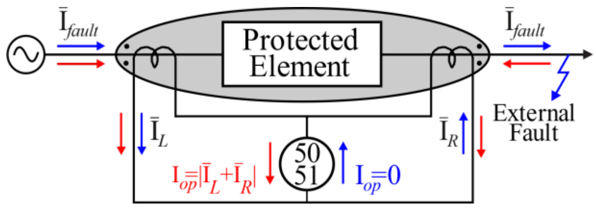

Fig. 4 PH87 element operation principle.

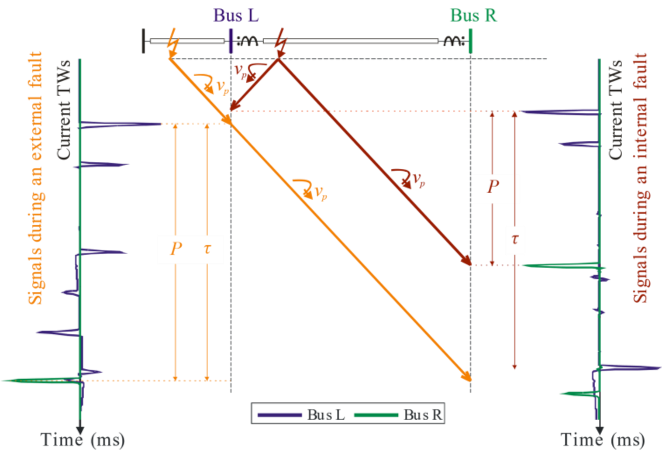

Fig. 5 TW87 element operation principle.

Considering the polarities of current transformers (CTs), as shown in Fig. 4, in external fault cases or during the normal operation of the system, local and remote currents present opposite polarities. Conversely, in internal fault cases, local and remote currents present the same polarity. Thus, operating quantities can be derived in PH87 from both local and remote currents to be compared against restraining quantities in order to detect internal faults. In Fig. 4, just to illustrate the PH87 operation principle, the operating quantity is calculated as the absolute value of the sum of measured local and remote currents, although a diversity of formulations and strategies can be used to detect internal faults. On the other hand, regarding the element TW87, from Fig. 5, traveling waves with the same polarity and time-spaced by a period P smaller than the line travel time τ are observed in internal fault cases, whereas they present opposite polarities in external fault cases, being spaced by a time equal to τ. As a result, operating and restraining quantities can be also derived to detect internal faults, as reported in [6]. Due to space limitations, details on possible implementations of the PH87 and TW87 functions are not presented here, but a vast literature regarding that is available, from which further information can be obtained.

4 Testing platform and Evaluated Relays

4.1 Test System

The power system shown in Fig. 6 was modelled using the PS Simul in order to carry out the proposed studies. It consists of a 500 kV/60 Hz transmission line (TL) 239 km long that connects a wind power plant (WPP) at Bus L to a Thevenin equivalent circuit at Bus R, which in turn represent the power network (PN).

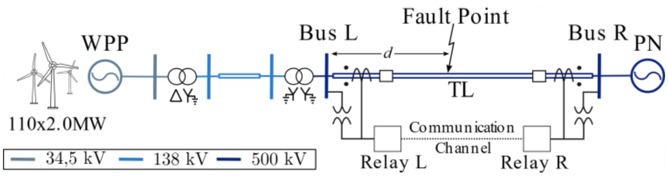

Fig. 6 Test power system

The evaluated TL was modelled using distributed parameter line model, constant in frequency, as fully transposed line. Besides, busbar stray capacitances of 0.1µF were considered according to [9], and the instrument transformers were modelled following the guidelines reported in [10] and [11]. The communication between the evaluated relays at local and remote TL terminals was accomplished by means of optical fiber-based channels, but the used fibers were very short, so that the channel latency was negligible. In addition, the turbines of the WPP were modelled in detail, covering nonlinear elements and associated controls. An average wind speed equal to 15 m/s was considered without any disturbance. The active and reactive powers supplied by the WPP were controlled at 220 MW and 0 MVAr, respectively.

All simulations were carried out using the PS Simul, which is a Brazilian EMTP software that allows an accurate representation of power/control systems and simulation of electromagnetic and electromechanical transients [7]. PS Simul has several components available that facilitate the modelling of converter-based systems and tools which optimize the simulation process, such as the snapshot tool which was used to accelerate the WPP simulation initialization. Such a tool allows the user to "freeze" the state of system at certain times of a simulation, aiming to start the next test from the point where such a freezing snapshot was taken. Hence, as the evaluated WPP model presents slow convergence, a snapshot was taken few cycles after its stabilization, speeding up the remaining simulations.

4.2 Testing set 1

Phasor-based protection functions were tested in a closed-loop system as depicted in Fig. 7. The records obtained from fault scenarios simulated via PS Simul were reproduced through a test box that injects signals at secondary levels in the protective devices, interfacing with them through channels that acquire generated binary signals. Thus, during the evaluation of phasor-based elements, each fault case was simulated considering a time-step equal to 10 µs, and then, voltages and currents were sent out from the computer to the test box CE-7012 [12], through which PS Simul generated signals were amplified and injected into the protective relays. Then, the test box receives back the relay tripping signals, which are in turn used to interact with the simulation.

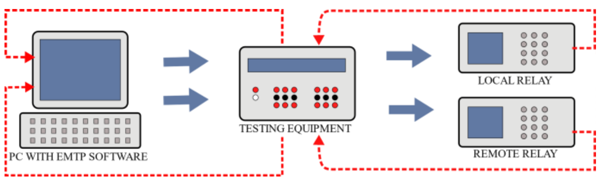

Fig. 7 Testing set 1.

4.3 Testing set 2

Fig. 8 shows the steps for testing the evaluated time-domain protection elements. Fault cases were firstly simulated considering a time-step equal to 1 µs, from which generated Comtrade files were converted into a specific format allowed by the playback functionality available in the analysed time-domain relay. As a result, 1 MHz records were directly loaded into the protective relay memory, guaranteeing proper representation of the traveling waves launched by the simulated faults.

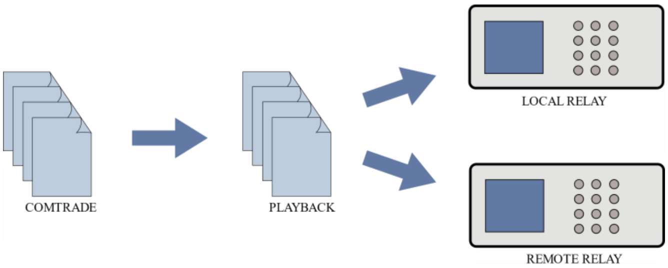

Fig. 8 Testing set 2.

4.4 Evaluated Relays

Relays from four different manufacturers were tested in this paper, focusing on the operation of distance and differential elements, as explained earlier. Three phasor-phased relays and one time-domain relay were taken into account. Due to confidentiality reasons, details on the functions embedded in each relay are omitted, being the phasor-based relays referred to as Relay 1, Relay 2 and Relay 3, and the time-domain relay as Relay 4. It is worthy emphasizing that all protective relays were configured following the manufacturer's instructions, and that the Relay 1 is not equipped with differential protection elements, so that only results regarding its distance protection are presented.

5 Results and Discussions

A total amount of 120 internal fault scenarios were evaluated, in which fault type (FT), fault inception angle (θ) (using a sinusoidal reference), fault location (FL) and fault resistance (Rf) were varied, as described in Table 1.

Table 1 Test Cases

Parameters	Values
FT	AG, AB, ABG, ABC
θ	0º, 90º
FL	10%, 30%, 50%, 70%, 90%
R_f	0 Ω, 5 Ω, 50 Ω

Figs. 9 and 10 illustrate the number of operations verified for the evaluated distance and differential protection elements, respectively, for both local and remote buses (being the WPP connected at Bus L, as explained earlier). It can be seen that the distance protection number of operations at buses L and R are very different, attesting a relevant impact of the WPP connection at bus R. One should bear in mind that distance protection is indeed not expected to operate in cases of faults beyond the reaching point (in this paper taken as 80% of the line length) and in high fault resistance cases. The same can be highlighted for the TW87, which is not expected to operate in cases of overdamped transients, such as for inception angles equal to 0^o or for high values of R_f. In fact, still analysing Figs. 9 and 10, it is verified that the differential protection elements do not present relevant differences between local and remote number of operations, being the Relay 4 the most affected due to the abovementioned reasons. However, the main result here is the comparison between local and remote terminals, from which the impact of the WPP connection can be compared to the operations taken from Bus R where traditional generation units are connected. Therefore, from the obtained results, it is concluded that the differential protection elements were less affected than the distance protection functions.

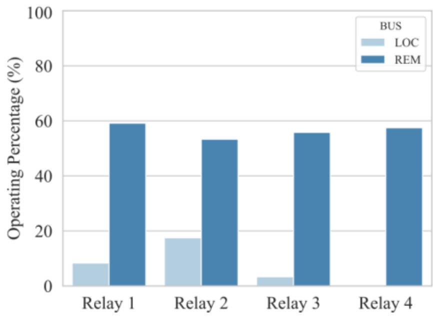

Fig. 9 Distance protection number of operations.

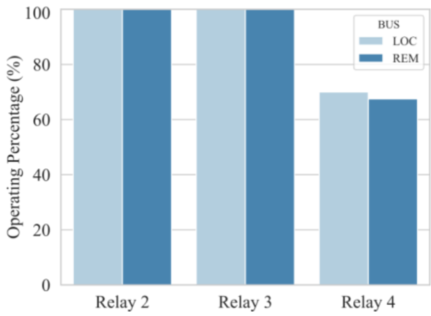

Fig. 10 Differential protection number of operations.

To further investigate the performance of the tested relays, Figs. 11 and 12 present the percentage of operations of the evaluated distance and differential protection elements as a function of the fault distance from the local bus. Again, it is observed that distance protection elements are relevantly affected at the WPP side, presenting a very reduced number of operations even for in-zone faults close to the measurement terminal, whereas at the traditional power network side, they operate in most cases, except when high fault resistance or out-of-zone faults are considered. An interesting result in Figs. 9 and 11 regards the time-domain distance protection, which detects the in-zone faults, but is restrained by the directional element supervision in all cases at Bus L. In addition, the differential protection elements have shown to be only slightly affected, being the Relay 4 the most affected. Indeed, such relay analyses current traveling waves, whose measurements are overdamped in the weak system terminal due to the high terminal impedance. As a result, the security layers restrain the relay operation for the sake of security.

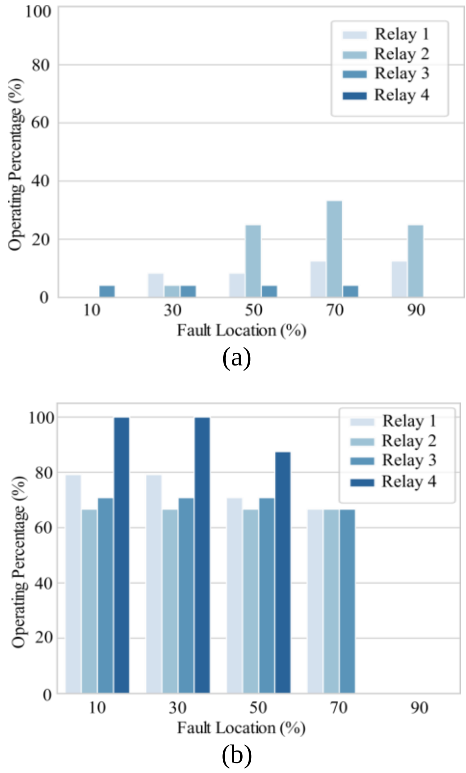

Fig. 11 Distance function operation varying fault location: (a) Bus L; (b) Bus R

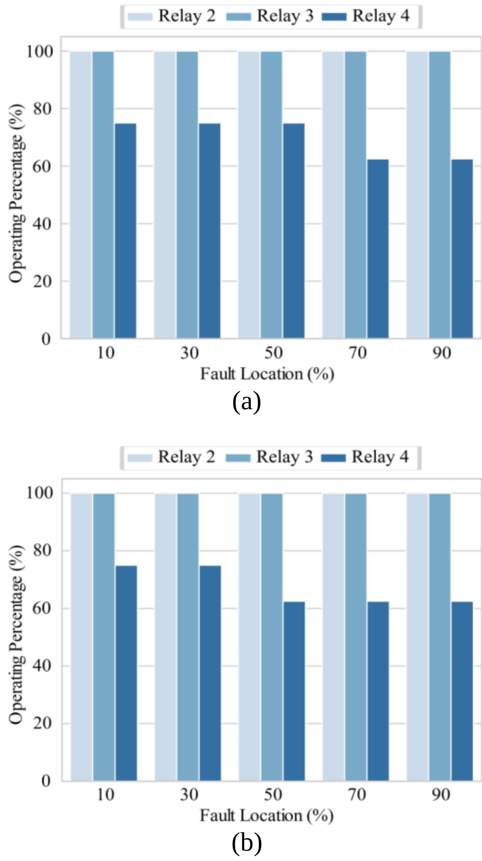

Fig. 12 Differential function operation varying fault location: (a) Bus L; (b) Bus R

Finally, Figs. 13 and 14 depict the operation times of the evaluated protection elements as swarm graphics, where each point represents a simulation case in which a tripping commands was issued. The results show that the Relay 4 was the fastest one, as expected for time-domain elements, but its distance element did not operate at Bus L. Regarding the remaining relays, it can be seen that additional operation delays of about a power cycle occurred at the WPP connection side (Bus L) in comparison to those observed at Bus R. In relays 1, 2 and 3, the distance protection functions were also the most affected elements, whereas the performance of the differential ones were only slightly influenced, irrespective of the analysed relay.

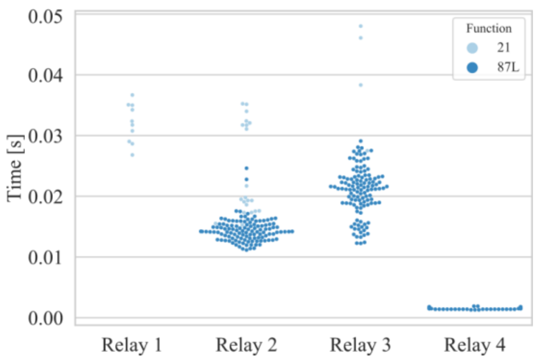

Fig. 13 Relays' operation times at Bus L.

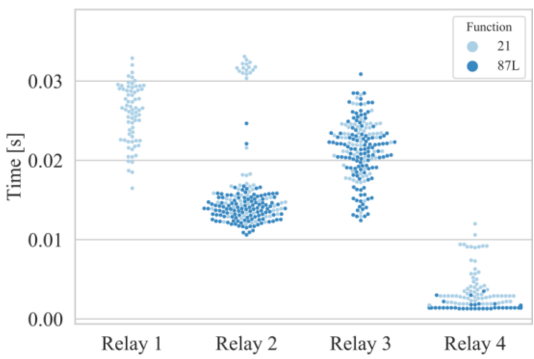

Fig. 14 Relays' operation times at Bus R.

Based on the presented results, it is concluded that the connection of converter-interfaced WPP indeed results in a challenging scenario for protection schemes, even for those based on time-domain procedures. The most critical issue is related to the number of operations, since the weak terminal leads protective relays to not operate in most cases. Differential elements showed to be a good alternative, being the use of pilot schemes also suitable to take advantage of the relays' operation at the traditional power grid side, where protection functions are expected to properly detect the fault. Thus, as all tests were performed using real relays equipped with technologies currently applied in the field, the need for further developments capable of guaranteeing reliable monitoring of transmission lines in the presence of WPP is highlighted, while the use of differential elements and pilot schemes is indicated as good solutions to improve existing protection schemes applied in transmission systems that interconnect converter-interfaced WPP.

6 Conclusion

In this paper, four micro-processed relays were evaluated considering fault cases on a transmission line which interconnects a power network (with traditional generation units) with a converter-interfaced wind power plant. A total of 120 fault cases were simulated to analyse the behaviour of phasor-based and time-domain distance and differential protection elements from the point of view of number of operations and operating times.

The results reveal that distance elements are quite affected in the present of wind power plants, mainly due to the low fault contributions. Even the analysed time-domain distance element was jeopardised, being restrained by the directional element security supervision, which was not able to identify forward faults due to the huge impedance seen in the weak terminal. On the other hand, differential elements resulted in satisfactory performance, being only slightly affected.

7 References

[1] Costa, J., Toledo, R., Gama, L., et al.: 'Investigation on Full-Converter-Based Wind Power Plant Behaviour During Short-Circuits', Workshop on Communication Networks and Power Systems, Brazil, pp. 1-4, 2019.
[2] Nelson, R. J.: 'Short-circuit contributions of full converter wind turbines'. PES T&D 2012. IEEE, May 2012. p. 1-5.
[3] Chavez, J. J., Popov, M., Novikov, A., et al.: 'Protection Function Assessment of Present Relays for Wind Generator Applications'. International Conf. on Power Systems Transients (IPST2019), Perpignan, France, pp. 1-6, 2019.
[6] Schweitzer, E., Kasztenny, B., Mynam, M. 'Performance of time-domain line protection elements on real-world faults', 69th Annual Conf. for Prot. Relay Engineers, p. 1-17, 2016.
[7] PS SIMUL: Software for Power System Modeling and Simulation of Electromagnetic Transients (in Portuguese), Conprove Engenharia, Industry and Commerce, 2019. [Online]: http://www.conprove.com.br/pub/i_ps_simul.html.
[8] Anderson, P. 'Power system protection', (Wiley, 1998).
[9] Zhang, G., Shu, H., Lopes, F. V., et al.: 'Single-ended travelling wave-based protection scheme for double-circuit transmission lines', International Journal of Electrical Power & Energy Systems, 2018, 97, pp 93- 105.
[10] IEEE Power System Relaying Committee. 'EMTP Reference Models for Transmission Line Relay Testing', [S.l.], 2004.
[11] Pajuelo, E., Ramakishna, M., Sachdev, G. 'Strengths and limitations of a new phasor estimation technique to reduce CCVT impact in distance protection', Electric Power Systems Research, vol.80, 2009.
[12] Pereira, P., Pereira Jr, P., Martins, C., Salge, G., Davi, M., Lourenço, G., Da Silveira, P., Guerrero, C., Reis Filho, F. 'Closed Loop Testing: A Comparison Between Real Time and Iterative Method (in Port.) ', SNPTEE, Brazil, 2017.