Noname manuscript No.
(will be inserted by the editor)

Authors' version. Available in:
http://link.springer.com/article/10.1007/s40313-021-00831-9

Busbar Capacitance Modeling Effects During Relay Testing Procedures for Transmission Lines Interconnecting Wind Power Plants

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Received: date / Accepted: date

Abstract In this paper, the performance of phasor- and time-domain-based line differential and distance protection functions is evaluated considering the presence of wind power plants (WPPs). In the proposed study, the impact of busbars capacitance modeling on relay testing procedures is investigated by analyzing real devices. The obtained results reveal that the busbar capacitance modeling is mandatory during tests of transient-based functions, being crucial for the correct protection analysis for lines interconnecting WPPs.

Keywords Busbar capacitance · phasor-based relays · protection systems · power systems · time-domain relays · transmission lines · wind power plants.

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1 Introduction

Modern power grids have evolved toward increasing the system flexibility of the applied generation sources, but reducing the system environmental impacts. As a result, renewable resources for electrical power generation have attracted the attention and interest from investors, being increasingly included in existing electrical power networks [1].

Among traditional renewable resources, WPPs have been widely used in several countries, as in Brazil, where major part of the Northeast region electric power demand has been supplied by wind turbines. It has boosted researches on protection, transients, control, and power electronics in the presence of WPPs [1–3]. Regarding the protection of transmission lines that interconnect WPPs to the grid, two main challenging scenarios are often reported: 1) converter-interfaced wind power generation units result in unconventional transient and short-circuit behaviors [1,2]; 2) weak terminals are usually verified at the WPP side, where power transformers are typically used to connect a single line, elevating voltages to the desired high levels at the power network side [2]. As the line terminals strengths can influence the protection functions [1], relay testing procedures are of great importance when WPPs are integrated to the grid.

As the WPPs affect the system behavior when faults take place on the connecting line, some modeling aspects frequently disregarded during classical short-circuit studies become crucial to guarantee reliable relay transient playback testing procedures, allowing fair conclusions on the protection performance. For instance, busbars capacitances C_{busbar} deserve attention, since a single-circuit line is typically connected at the WPP side by means of power transformers, which result in a predominantly inductive high impedance termination. Thus, disregarding C_{busbar} in simulations can lead high frequency components to see a quasi open-circuit at the WPP side [4], improperly emulating attenuated current transients.

Although the influence of C_{busbar} on phasor-based protection is usually assumed to be negligible, a quantitative analysis considering real protective relays as well as studies on their influence during playback tests of transient-based protection functions (as the time-domain-based ones) is still scarce in the literature. Thereby, this paper evaluates the performance of three phasor-based relays and one time-domain relay, taking into account a typical WPP connection topology, considering and not considering the C_{busbar} modeling at the line terminals. To do so, type IV (full-converter) WPP units are taken into account. This type of WPP model is fully interfaced by converters, resulting in the most critical scenarios from the point of view of fault current contribution and power electronics influence. For each case, fault features are varied and the performance of differential and distance protection functions are assessed. Besides, a sensitivity analysis on the C_{busbar} value is carried out in order to demonstrate the importance of accurately modeling the busbar capacitances during the evaluation of protection functions applied to very weak terminals, such as commonly verified in typical WPPs connection circuits. The results demonstrate that the C_{busbar} modeling can influence the behavior of all analyzed protection elements, but it shows a more critical effect on time-domain functions that require the analysis of high-frequency components, such as the traveling wave-based ones.

2 Considerations on Wind Power Plant Modeling, Simulation and Relay Testing

2.1 Typical Connection Circuit Topology

WPPs operate with low voltage levels at their terminals, so that they are usually equipped with step-up transformers that elevate voltages from few hundreds of volts to medium voltage levels. To connect WPPs to the remaining power network, most systems apply a delta-wye connected transformer to obtain sub-transmission voltage levels. Then, a second transformer is employed to elevate voltages to transmission levels, being this equipment typically an autotransformer with wye-wye connection grounded at both sides.

The above-mentioned topology is illustrated in Fig. 1, in which the position of each referred equipment can be seen. It should be noticed that the equivalent impedance behind the WPP connection bus (in the figure, Bus L) tends to be much larger than the line impedance and also than the equivalent impedance beyond the remote terminal (in the figure, Bus R). Therefore, although a strong zero sequence current path is verified in single-phase fault cases due to the wye-grounded connected transformers [8], low fault current contributions are expected to come from the WPP. Such a behavior can be further aggravated if converter interfaced WPPs are considered, in which the control schemes usually limit fault currents, also changing these quantities in accordance to the applied control methodologies. Hence, the system behavior during short-circuits differs from the one observed when the classical synchronous machine models are used to represent generation sources, posing difficulties for traditional protection studies. Therefore, in this paper, the evaluated test power system follows the typical WPP connection circuit topology shown in Fig. 1, allowing a proper representation of the unconventional power system behavior under fault conditions.

2.2 Test Power System and Simulations

The analyzed test electrical power system is modeled as illustrated in Fig. 1. It allows a suitable representation of the WPP connection circuit topology, as stated in the previous subsection. Here, the WPP connection to the remaining electrical power network (referred in the figure as PN) is made by using a 500 kV/60 Hz transmission line (referred as TL), 239 km long, which will be the focus of the protection studies presented throughout the next sections. For the sake of simplification, local bus (Bus L) is assumed to be the line end where the WPP is connected, where a weak terminal is verified. On the other hand, the remote bus (Bus R) is taken as the connection point to the power grid, which is represented by a Thévenin equivalent circuit, whose data were obtained from short-circuit studies in a real Brazilian electrical power system.

All fault scenarios evaluated in this paper were simulated by using the PS Simul software [9], which consists of an EMTP Brazilian program that has several electromagnetic transient models available for studies that require the emulation of signals instantaneous values. Therefore, the analyzed WPP turbines were modeled including nonlinear elements and their associated controls by means of a Type IV model available in the PS Simul models library [9], allowing the representation of the power electronics impacts on the studied protection functions. An average wind speed equal to 15 m/s was considered and no wind disturbance was simulated, being the active and reactive powers supplied by the WPP controlled at 220 MW and 0 MVAr, respectively. Hence, the differences between one fault simulation to another consisted of variations in fault features and the presence or not of the busbars capacitances C_{busbar}.

In the test power system, the transmission lines were modeled using the fully transposed Bergeron line model, and the power transformers models were adjusted using typical values obtained from real WPPs. Also, evaluated signals were taken from capacitive voltage transformers (CVT) and current transformers (CTs), which were modeled as reported in [5] and [10], respectively. The CT computational model

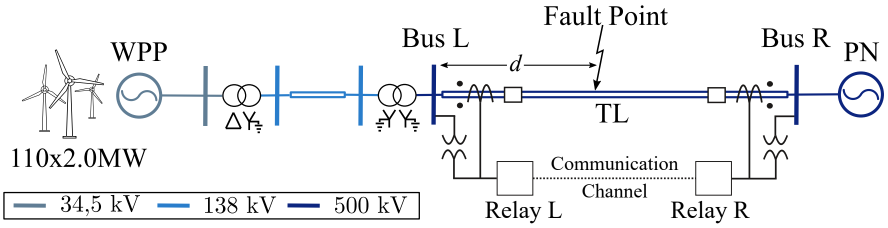

Fig. 1 Test power system considering traditional WPP connection circuit topology.

presents linear frequency response in a wide spectrum range, so that it is not an issue for the test cases shown here [5, 10]. On the other hand, the used computational CVT model has limited frequency response bandwidth, being suitable only for studies on protection functions based on low frequencies, such as the fundamental one. To avoid misinterpretations on the analyzed transient-based protection elements, only functions that depend mainly on current high-frequency signals were assessed. Moreover, to properly represent the signals of interest for both types of protection functions, simulation time steps of 10 μs and 1 μs were taken into account during the evaluation of phasor- and time-domain-based protective relays, respectively. It is worthy to mention that, although the analyzed fault records are taken from simulations, all the results are obtained from playback tests using real relays, i.e., no protection algorithm was required to be implemented externally to the analyzed devices. In Fig. 1, the point on the system at which the evaluated relays are assumed to be installed is indicated, being the pairs of each relay model analyzed one at a time, i.e., relays shown in the figure can represent different models.

2.3 Busbar Capacitances C_{busbar}

This paper is mainly focused on the demonstration of the busbar capacitance C_{busbar} modeling influence on protective relays responses during playback tests aimed to assess monitoring solutions for transmission lines that connect WPPs to the power grid. Hence, the goal here is to highlight the importance of C_{busbar} modeling, mainly when protection elements based on high frequency components are applied, such as the traveling wave-based ones. As it will be demonstrated in the next sections, not modeling C_{busbar} can unfairly condemn protection functions and, thus, it should be avoided. Therefore, analyzing the C_{busbar} influence on real protective devices is an enlightening study that can clarify these issues, allowing the proper identification of C_{busbar} modeling requirements for each type of protection solution.

During studies on transmission line fault-induced transients, amplitude and polarity of traveling waves launched from the fault point that are measured at the line ends depend on the characteristics of both line terminations [11]. When busbars have more than one line connected, the influence of line terminations is mostly related to the lines' surge impedances, being the effects of other high-impedance equipment less evident. As a result, line termination is more reflective for current waves, preserving information on their amplitudes and polarities [4]. On the other hand, when there is only one line connected through a power transformer on a given busbar, as shown in Fig. 1, there is a restricted path through which fault-induced current traveling waves can propagate, except whether busbar capacitances C_{busbar} are considered. Thus, it reinforces the importance of analyzing the C_{busbar} modeling effects on WPP interconnection circuits when relay testing procedures are carried out using EMTP simulated fault records.

Typical C_{busbar} values may vary from 2000 pF to 0.1 μF [4, 12]. Here, phase-to-ground stray capacitances of 0.1 μF are modeled at buses L and R in the test power system for a first set of testing cases, following procedures reported in [12]. These capacitances are then varied to allow a protection performance sensitivity analysis, as it will be detailed in the following sections. Figs. 2 to 5 compare phase A voltage and current signals obtained from a solid phase A-to-ground fault simulation at the middle of the line initiated at the voltage peak, considering the simulated test system with and without C_{busbar}. It can be seen that at steady-state, no relevant deviations between signals captured from the test system in both scenarios are verified. However, during the fault period, transients induced in voltage and current waveforms present significant differences, being more evident in current signals when C_{busbar} is taken into account. Indeed, when the C_{busbar} is considered, traveling waves that reach the transmission line terminals see a termination which behaves initially as a short-circuit, quickly evolving to quasi open-circuit. Such a characteristic favors the measurement of current transients, but attenuates voltage ones. Then, when the fault enters into a steady-state condition, both voltage and current signals tend to be coincident, presenting only slight deviations due to spurious undamped transients.

As a consequence of the above-mentioned transient patterns, it is expected that fundamental component-based protection functions are not relevantly affected by the busbar capacitance C_{busbar}, except by the influence of transient content that may yield additional oscillations in the estimated

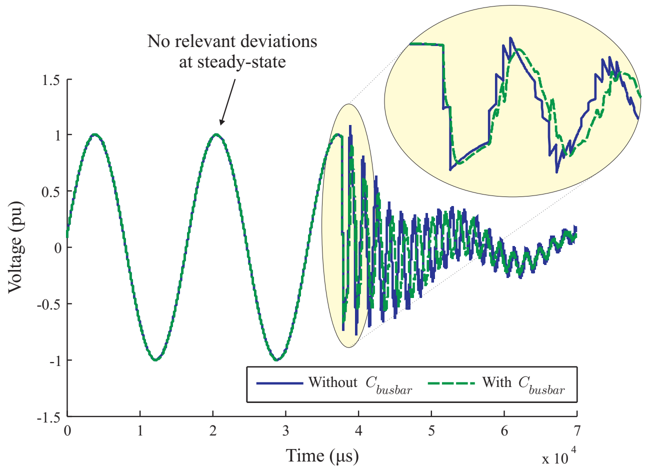

Fig. 2 Local voltage signals with and without C_{busbar}.

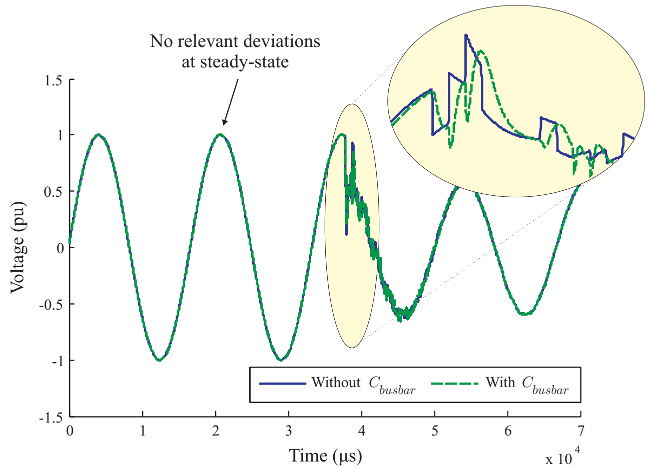

Fig. 4 Remote voltage signals with and without C_{busbar}.

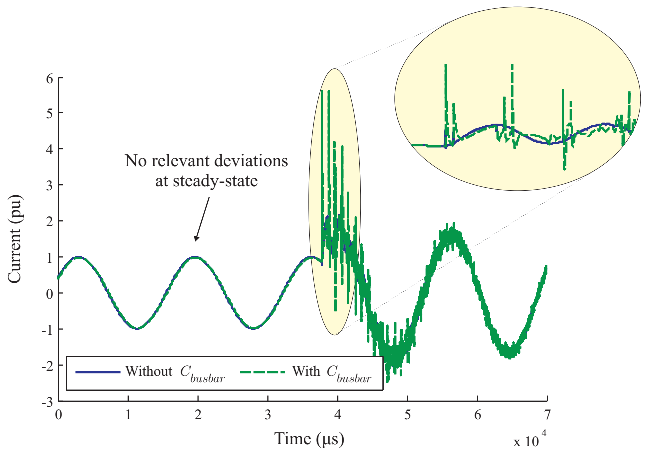

Fig. 3 Local current signals with and without C_{busbar}.

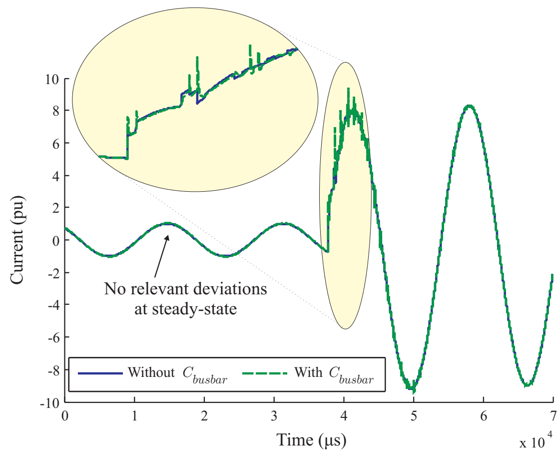

Fig. 5 Remote current signals with and without C_{busbar}.

phasors. In fact, despite the use of full cycle approaches to estimate the fundamental component, these filters are affected by sub-synchronous and inter-harmonic components, which may show up especially at the WPP side. Even so, transient-based functions are more prone to change their operation performances than the phasor-based ones, especially those that depend on the analysis of traveling waves.

2.4 Relay Testing Procedures

In order to test phasor- and time-domain-based relays, different testing methodologies had to be used, such as illustrated in Fig. 6. In the case of phasor-based relays, high-frequency spectrum content is eliminated by anti-aliasing filters and by phasor estimation algorithms, so that there is no need to represent transients in the order of hundreds of kilohertz, considering the test system with and without C_{busbar}. Thus, the test set CE-7012 [7] was used to inject signals taken from the PS Simul simulations at secondary levels in the evaluated protective devices, guaranteeing the proper representation of transients up to few kilohertz. Nevertheless, as such a spectrum representation is not enough to properly evaluate transient-based functions, the playback test functionality available in the analyzed time-domain relay was taken into account [6]. From such a functionality, PS Simul generated records considering the test system with and without C_{busbar}, which were directly loaded into the relay memory. Then, these records were played back into the relays, guaranteeing the proper representation of transients in the order of hundreds of kilohertz. It should be emphasized that such functionality is not available in the evaluated phasor-based relays, so that it has been applied only to the time-domain relay. Even so, as explained before, the frequency spectrum ranges evaluated by each relay were fully considered, in such a way that reliable studies on the impact of C_{busbar} could be performed.

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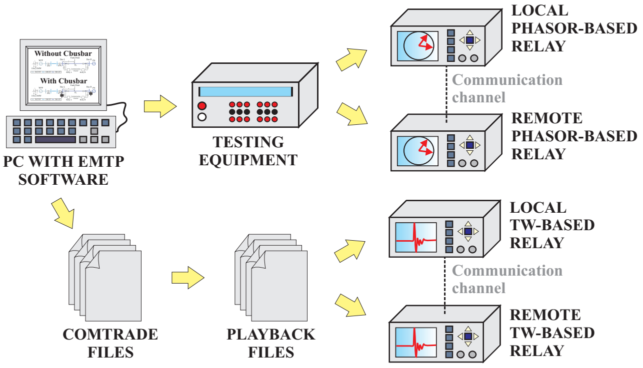

Fig. 6 Testing assembly to evaluate the performances of relays considering the test system with and without C_{busbar}.

3 Studied Cases and Obtained Results

Due to confidentiality reasons, the evaluated relays are referred to in this paper as Relay 1, Relay 2, Relay 3 and Relay 4. It must be pointed out that Relays 1, 2 and 3 are equipped with phasor-based functions, whereas Relay 4 has time-domain high-speed elements, among which a distance element based on instantaneous incremental quantities and a differential element based on traveling waves are analyzed. Distance protection (21 function) was evaluated in all relays, whereas the differential protection (87 function) was tested only in Relays 2, 3 and 4, because Relay 1 is not equipped with such function. These protection elements were chosen because they have been the most used worldwide to protect transmission lines, including those that interconnect WPPs to the power grid.

To evaluate these functions individually, pilot schemes were kept disabled. Besides, since the tested relays were installed in the same rack during the accomplished studies, the communication between local and remote devices during the laboratory tests was accomplished by means of a short optical fiber (few meters only), so that the channel latency effect is not included in the obtained results. It is also worthy to mention that, in all cases, the protection operation times were measured in relation to the fault inception instant. To do so, auxiliary signals that represent the fault switch status were included in the generated records, allowing the posterior comparison with the obtained tripping signals.

Aiming to present comprehensive results, fault features were varied considering: fault distances d equal to 10%, 30%, 50%, 70% and 90% of the line length from Bus L (local bus), fault inception angles θ equal to 0 and 90 degrees assuming a sinusoidal reference (angles close to zero represent voltage zero-crossing cases), fault resistances R_f equal to 0 Ω (solid faults), 5 Ω and 50 Ω, and different fault types, namely, AG, AB, ABG and ABC. In each case, the number of operations and the operation time of the analyzed protection functions at both local and remote buses

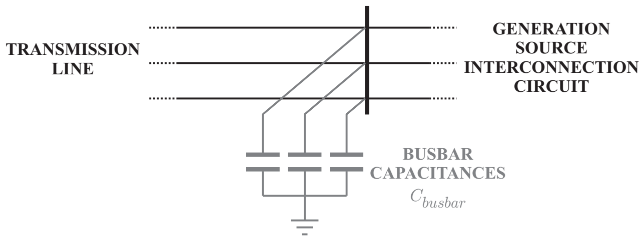

Fig. 7 C_{busbar} representation.

with and without $C_{busbar} = 0.1$ μF were firstly evaluated. Since the transmission line model already includes mutual capacitances between the line phases, C_{busbar} was modeled considering wye-connected capacitors connected from the busbar to the ground, as shown in Fig. 7.

3.1 Number of Operation

Figs. 8 and 9 present the number of operations of the 87 and 21 protection elements available in the evaluated protective relays, respectively. Operations at both local and remote line terminals were accounted for, considering and not considering the C_{busbar} modeling effects. Such an analysis allows the investigation of the relays' reliability when the C_{busbar} modeling is and is not taken into account, as well as the comparison between the protection performance at both WPP and power network sides.

From Fig. 8, it can be seen that differential protection elements available in Relays 2 and 3 operated for 100% of the analyzed fault scenarios at buses L and R, being not affected by the C_{busbar} modeling. It demonstrates that phasor-based differential protection functions are reliable even when a weak termination exists, as in the WPP terminal in the test power system. Moreover, these results prove that the C_{busbar} modeling is not critical when phasor-based differential protection functions are under investigation, so that simplified test system EMTP modeling would be acceptable for relay testing procedures. On the other hand, considering the time-domain Relay 4, the C_{busbar} modeling showed to be a critical question, since no operation was verified when C_{busbar} was disregarded. Indeed, as a power transformers is the first equipment seen by traveling waves that reach the busbar at the WPP side, high-frequency components see a quasi open-circuit. It results in a negative reflection coefficient for current traveling waves [11], leading measured wavefronts to present high attenuation levels. As a consequence, the amplitudes of measured current traveling waves are not enough to sensitize the time-domain differential element, restraining it when C_{busbar} is not considered. However, by including the C_{busbar} effects, the amplitude of measured current traveling waves increase, allowing the proper fault detection in about 70% of the simulated cases. Such a result is coherent, since the remaining 30% of simulated scenarios are mostly related to faults with θ close to 0 degrees, consisting in cases in which traveling waves are not launched on the line.

Analyzing the Fig. 9, as already reported in the literature, a critical performance of the 21 protection elements is verified at the WPP side, where the relays operated in very few cases. At Bus L, distance protection available in Relays 1, 2 and 3 operated in a number of cases which did not exceed 10%, 20% and 5%, respectively, whereas no operation of the distance element available in Relay 4 was observed. Although some measures could be taken to improve the performances of these protection schemes [8], the main focus here is on the analysis of the C_{busbar} modeling impact on the evaluated elements. Therefore, it must be noticed that the results do not change significantly when C_{busbar} is and is not taken into account, which is the same conclusion obtained when the results from Bus R are evaluated. Indeed, at the remote terminal, distance protection elements operated for a number of cases of about 60% of the simulated fault scenarios, demonstrating that the relays underreached in some cases, since an 80% (of the line length) reach setting was used. However, from the point of view of the C_{busbar} influence, modeling it was not decisive for the operation performance of the evaluated distance protection elements.

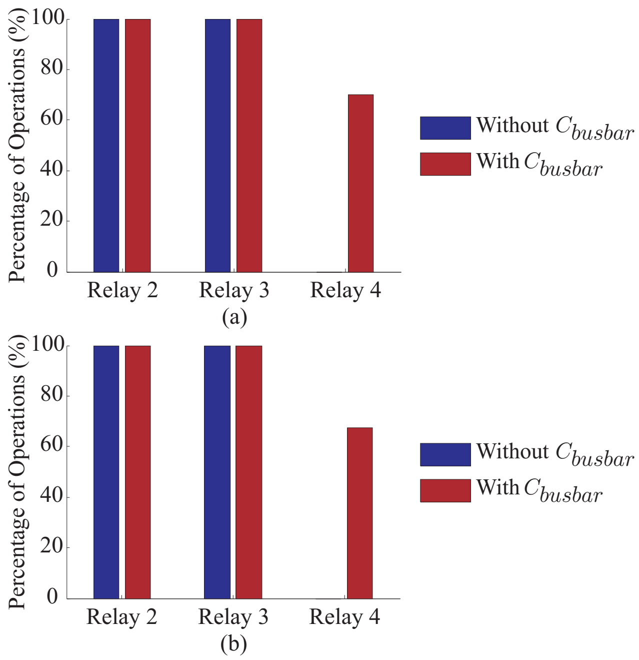

Fig. 8 Number of differential element (87 function) operations at: (a) Bus L (WPP side); (b) Bus R (PN side).

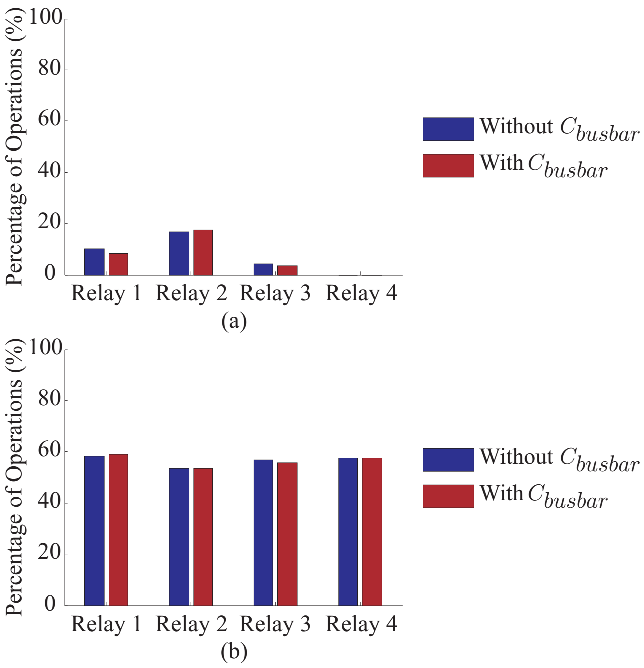

Fig. 9 Number of distance element (21 function) operations at: (a) Bus L (WPP side); (b) Bus R (PN side).

3.2 Operation Times

Figs. 10 to 13 illustrate boxplots that represent basic statistics of the operation times obtained from cases in which Relays 1, 2, 3 and 4 operated[1]. The boxplots present: the maximum and minimum values, represented by the upper and lower whiskers, respectively; the upper quartile (75th percentile), represented by the upper boundary of the box; the median (50th percentile), represented by the central line inside the box; the lower quartile (25th percentile), represented by the lower boundary of the box; and the outliers, which represent cases in which operation times with relevant differences in relation to the remaining scenarios were found. For each relay, two boxplots are presented, being each related to the results obtained when C_{busbar} is and is not considered.

Figs. 10 and 11 show that the C_{busbar} modeling is not critical for protection studies regarding the operation times of phasor-based functions. For the 87 protection element, the inclusion of C_{busbar} resulted only in few different outliers in the boxplots of Relays 2 and 3. In addition, from Figs. 12 and 13, one can observe some differences in the operation times of the 21 elements available in Relays 1, 2 and 3, being more relevant at the WPP side and negligible at the remote transmission line end. Even so, none of these variations would lead to a misinterpretation on the protection performance, demonstrating that the C_{busbar} modeling is not a critical issue for phasor-based relays.

Regarding the time-domain functions, the 21 element available in Relay 4 was not relevantly affected by the C_{busbar} modeling as well. It is worthy to mention that this relay is

[1] The term 'NO OPERATION' is used only when the protection function did not operate in none of the evaluated cases.

designed to be fast in critical short-circuit scenarios, when current fault levels are dangerous for the system integrity, which is not the case of the evaluated scenarios, in which quite reduced fault current contributions come from the WPP. Hence, the relay 21 function restrained in all cases at the WPP terminal (Bus L), but presenting a stable behavior at Bus R, irrespective of the C_{busbar} modeling. On the other hand, as mentioned earlier, the C_{busbar} modeling showed to be important during the evaluation of the traveling wave-based 87 element available in Relay 4, since such function operated only when C_{busbar} was taken into account. Thus, the general conclusion is that the C_{busbar} modeling can influence protection elements, but it is critical only when transient-based schemes are under investigation. Indeed, the number of operations of these functions can drastically change simply by including or not the C_{busbar} in the used EMTP modeling environment, which can lead to unfair conclusions on the protection scheme reliability if C_{busbar} is disregarded.

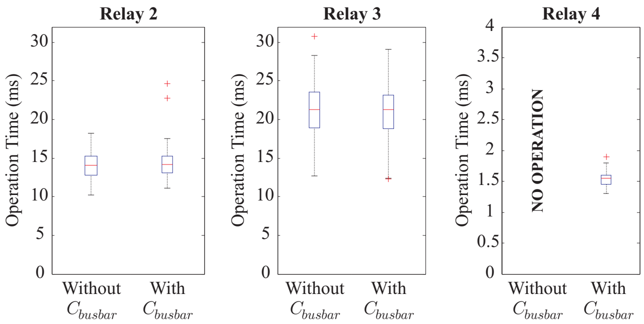

Fig. 10 Boxplots of 87 protection operation times at Bus L (WPP side).

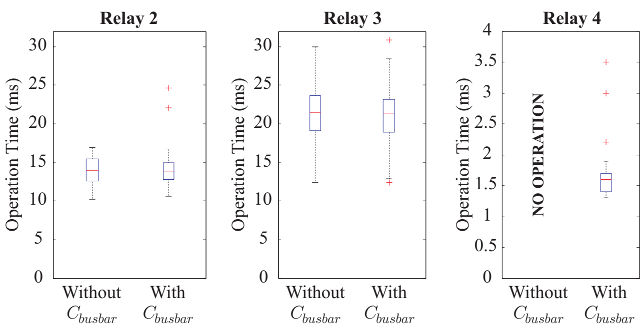

Fig. 11 Boxplots of 87 protection operation times at Bus R (PN side).

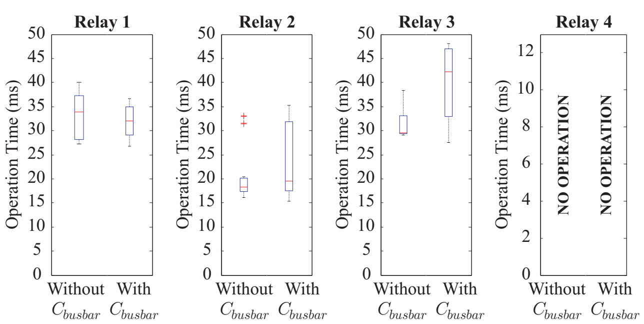

Fig. 12 Boxplots of 21 protection operation times at Bus L (WPP side).

3.3 Traveling Wave-Based Protection Sensitivity Analysis Considering Different C_{busbar} Values

From the previous results, it was concluded that the C_{busbar} modeling is not critical for phasor-based protection functions from the point of view of number of operations. Even the analyzed incremental quantity-based distance protection element has shown to not be relevantly affected by different C_{busbar} modeling strategies. Indeed, the most critical results were verified when the traveling wave-based 87 protection element was considered, since it requires the analysis of high frequency components which are influenced by C_{busbar}.

In the first set of case studies, $C_{busbar} = 0.1\ \mu$F was taken into account. However, it is known that such a busbar capacitance value may vary, depending on the power system rated voltage, busbar layout, and conductors features. Thus, this section presents a sensitivity analysis in which the C_{busbar} value is varied from 0 (without busbar capacitance) up to 100 nF (equivalent to the value in the previous section, i.e., $C_{busbar} = 0.1\ \mu$F), with steps of 5 nF. By doing so, it becomes possible to verify the C_{busbar} influence on the traveling wave-based 87 element operation time, also identifying the minimum C_{busbar} value that guarantees the protection operation in the analyzed test power system. Furthermore, to provide a more comprehensive understanding on the C_{busbar} effects on different fault scenarios, two fault resistances R_f values are considered, namely $R_f = 0\ \Omega$ (solid fault) and $R_f = 50\ \Omega$, being three different fault distances simulated, i.e., $d = 10\%$, 50% and 90% of the line length, accounting the distance from the local bus.

The results obtained by applying the protection functions to signals taken from buses L and R are presented in

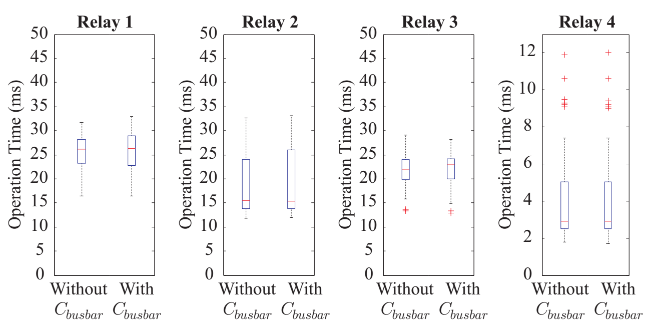

Fig. 13 Boxplots of 21 protection operation times at Bus R (PN side).

Figs. 14 and 15, respectively. In both figures, the absence of markers represent the cases in which the protection elements remained stable, i.e., no operation was verified. Therefore, from the presented results, it can be seen that, in the analyzed test system, small C_{busbar} values can lead the protection to restrain, which can be a not very realistic scenario, depending on the analyzed system.

Still analyzing Figs. 14 and 15, one can see that, by increasing C_{busbar}, and if the protection minimum wavefront amplitude condition is met, variations in relay operation times are not significant, irrespective of the fault resistance for a given fault distance. Indeed, in the analyzed test system, the traveling wave-based 87 function started to operate when C_{busbar} values greater than or equal to 20 nF were considered, being such a behavior observed at both line ends. In addition, the operation time deviations for specific fault distances did not exceed the order of 0.1 μs when C_{busbar} was increased, which is considered a negligible variation, even for ultra-high-speed protection functions.

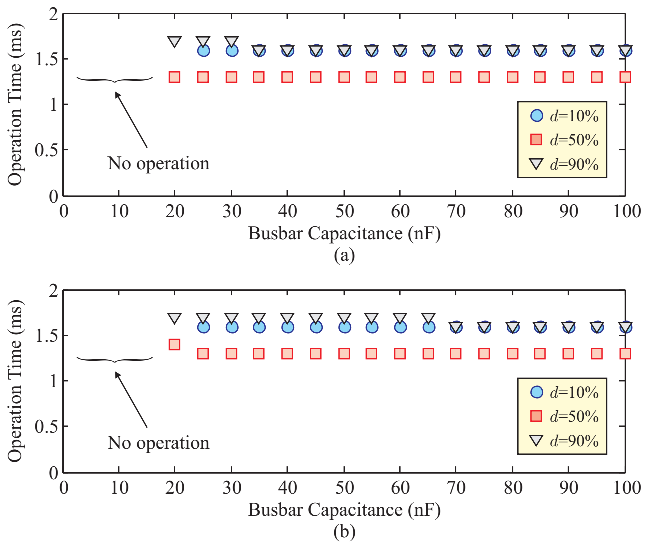

Fig. 14 Operation times per busbar capacitances at Bus L (WPP side): (a) $R_f = 0\ \Omega$ (solid fault); (b) $R_f = 50\ \Omega$.

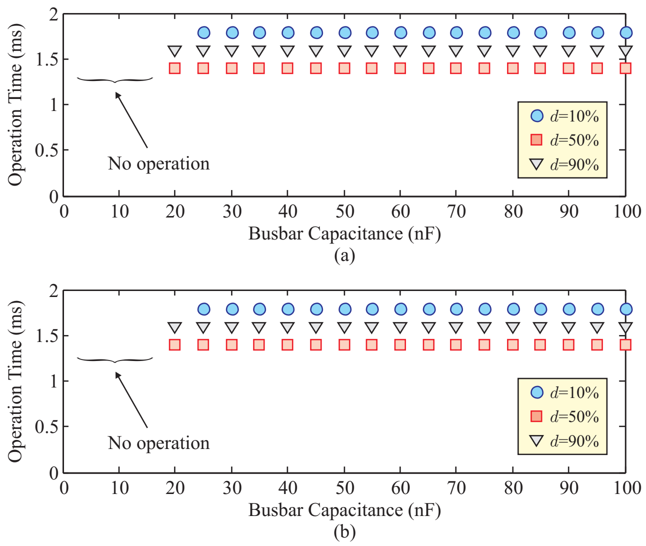

Fig. 15 Operation times per busbar capacitances at Bus R (PN side): (a) $R_f = 0\ \Omega$ (solid fault); (b) $R_f = 50\ \Omega$.

From an overall perspective, it is concluded that there is a minimum C_{busbar} value that guarantees the traveling wave-based protection operation at the WPP side. Hence, the question that arises from this conclusion is: Can we consider that the real busbar capacitance value is enough to lead the transient-based protection to operate? In the authors opinion, the only way to respond to this question is by performing a thorough analysis on the busbar characteristics in order to obtain an accurate representation of C_{busbar}. From some studies regarding real systems, the authors could verify that power grids with the same characteristics of the tested one would result in busbar capacitances with values sufficient to sensitize the evaluated differential transient-based protection function. Nevertheless, it is worthy to point out that this paper does not aim to explain if a given transient-based protection function is dependable or not, but rather, it is intended to demonstrate that an improper power system modeling during playback testing procedures based on EMTP generated records can result in completely unrealistic interpretation on the protection performance. Thereby, the main conclusion is that the C_{busbar} accurate modeling is mandatory in power systems like the one evaluated in this paper, i.e., in which lines interconnecting WPPs exist, specially if traveling wave-based elements are under investigation. Otherwise, even if these transient-based protection solutions come to be beneficial in real life, they could be unfairly disapproved for field applications, which is undoubtedly undesirable, specially for systems where traditional functions present a limited performance.

4 Conclusions

In this paper, an evaluation on the influence of the busbar capacitance modeling during protection devices testing for transmission lines that interconnect wind farms to the power grid was presented. As the typical connection topology consists of series power transformers with a single-circuit line connected at the monitored busbar, stray capacitances become an important modeling issue to be considered during relay testing procedures that use EMTP-generated records, mainly when transient-based solutions are under investigation.

The PS Simul program was used to simulate faults on a typical wind power plant connection system. A 500 kV/60

Hz line was modeled, considering Type IV wind power generation units at one line terminal, and a typical power network at the opposite side. Four real protective relays were evaluated, considering differential and distance protection elements based on phasor quantities and on instantaneous values of monitored signals. Among the relays, three are equipped with phasor-based functions, and one with time-domain elements, such as a traveling wave-based differential function, and an instantaneous incremental quantity-based distance protection algorithm.

From the obtained results, the first conclusion is that the busbar capacitance modeling is critical when transient-based functions are under investigation, specially at the wind power plant side where a power transformer is connected. Indeed, such an equipment is seen by high frequency components as a quasi open-circuit. As a result, voltage high frequency transients at the weak terminal tend to be stronger, but current transients tend to be highly attenuated, jeopardizing the operation of current traveling wave-based functions, such as the tested traveling wave-based 87 element. On the other hand, from a point of view of the number of operations, no relevant differences were observed in the performance of phasor-based 87 elements and phasor- and time-domain-based 21 functions when the busbar capacitance is and is not considered. Indeed, as these elements analyze signals within the inferior spectrum range, the busbar capacitance effect is not significant, leading the weak fault contribution from the wind farm to be the most critical problem.

Regarding the relays operation times, no relevant influence of the busbar capacitance modeling on phasor-based protection functions was verified. Operation times of phasor-based 87 elements were not significantly affected, and despite the variations verified in the 21 protection operation times, none of the results would lead to a misinterpretation on the protection reliability. The same conclusion could be drawn regarding the 21 time-domain protection element, whose operation times did not present relevant variations when the busbar capacitance was and was not modeled.

Since the traveling wave-based function has shown to be the most critically affected by the busbar capacitance modeling in the evaluated system, additional cases were tested to carry out a sensitivity analysis, through which the traveling wave-based 87 protection operation time was analyzed in relation to the busbar capacitance value. The results reveal that there is indeed a minimum busbar capacitance value from which the traveling wave-based elements are expected to operate. This finding highlights the need for careful EMTP system modeling during the evaluation of traveling wave-based functions when applied to very weak terminals, as it occurs in wind farm connection busbars. Otherwise, results can significantly affect the protection performance understanding due to a modeling aspect. It can lead transient-based protection elements to be unfairly condemned, depending on the system, even if they are beneficial to the power network, which is a mistake that obviously must be avoided during relay testing procedures.

Acknowledgements The authors would like to thank Conprove Engineering, Industry and Commerce for the technical support during the simulations using the PS Simul software.

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