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# Transmission Line Protection Performance in the Presence of Wind Power Plants: Study on the Busbar Capacitance Modeling During Relay Testing Procedures

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**Abstract:** In this paper, the performance of transmission line differential and distance protection functions available in phasor- and time-domain-based relays is evaluated considering the presence of wind power plants. In the proposed study, an investigation on the system busbars capacitance modeling during relay testing procedures is carried out, indicating differences verified in the number of operations and operation times of four real protective relays. The obtained results reveal that the busbar capacitance modeling is critical for some protection functions, affecting mainly the reliability of transient-based algorithms.

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

## 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 sources have attracted the attention and interest from investors, being increasingly included in existing power networks (Chavez et al., 2019).

Among traditional renewable sources, wind power plants (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, electromagnetic transients, control, and power electronics in the presence of WPPs (Chavez et al., 2019; Costa et al., 2019; Blaabjerg and Ma, 2013). Regarding the protection of transmission lines that connect 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 (Chavez et al., 2019; Costa et al., 2019); 2) weak terminals are usually verified at the WPP side due to the power transformers that elevate voltages to the desired high levels at the power network side (Costa et al., 2019). As these features can influence the performance of existing protection functions (Chavez et al., 2019), relays testing procedures are of great importance when wind power integration is taken into account.

Since the system behavior is affected by WPPs when a fault takes place on the connecting transmission line, some modeling aspects that are frequently disregarded during traditional short-circuit and transient studies become crucial to guarantee reliable relay transient playback testing procedures. For instance, busbar capacitances deserve attention, since: only one line is connected at the WPP side; and connecting power transformers result in a high impedance termination. As a result, the terminal is seen by high frequency components as a quasi open circuit (Zhang et al., 2018), and thereby, disregarding busbar capacitances can change measured fault-induced transients, influencing the line protection.

Although the influence of busbar capacitances on phasor-based protection is usually considered negligible, a quantitative analysis considering real 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. Hence, this paper evaluates the performance of three phasor-based relays and one time-domain relay, considering a typical WPP connection topology, with and without busbar capacitances modeled at the line terminals. For each scenario, fault features are varied and the performance of differential and distance protection functions are assessed. The results show that busbar capacitance modeling can affect both phasor-based and time-domain protection elements, being more critical for time-domain functions based on traveling waves.

## 2. CONSIDERATIONS ON WIND POWER PLANT MODELING, SIMULATION AND RELAY TESTING

### *2.1 Typical Connection Topology*

Wind power generation units 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 wind farms to the remaining power network, most systems apply firstly a delta-wye connected transformer to obtain sub-transmission voltage levels, and then, to elevate voltage to transmission levels, a second transformer is employed, which is typically an autotransformer with wye-wye connection. In this paper, the evaluated test power system follows such typical topology in order to properly represent the system behavior under fault conditions.

### *2.2 Test Power System and Simulations*

Fig. 1 presents the analyzed test power system, which represents the typical connection topology described in the previous subsection. The WPP connection to the remaining 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 in turn is the focus of the protection studies presented in this paper. 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 Thevenin equivalent circuit, whose data were obtained from short-circuit studies in a real Brazilian system.

All fault scenarios evaluated in this paper were simulated by using the PS Simul software (Conprove Engineering et al., 2019), which consists of an EMTP Brazilian program that has available several models for transient studies. Therefore, the WPP turbines were modelled including nonlinear elements and their associated controls by means of a Type 4 model available in the PS Simul software (Conprove Engineering et al., 2019), allowing also 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, which will be referred from now on as $C_{busbar}$. All 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 and current transformers, which were modeled as reported in Pajuelo et al. (2010) and Committee et al. (2004), respectively. Simulation time steps of 10 $\mu$s and 1 $\mu$s during the evaluation of phasor- and time-domain-based protective relays were taken into account, respectively, allowing the proper representation of the transient spectrum of interest during the testing procedures.

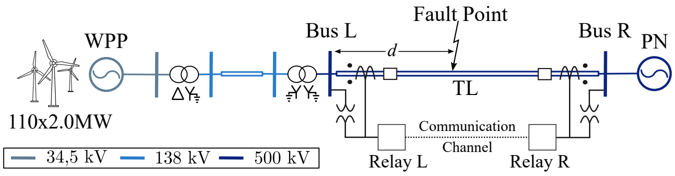


Figure 1. Test power system.

### *2.3 Busbar Capacitances*

During studies on transmission line fault-induced transients, amplitude and polarity of traveling waves measured at the line ends depend on the characteristics of both line terminations (Greenwood, 1991). When busbars have more than one line connected, the influence of line terminations is mostly related to the conductors, 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 (Zhang et al., 2018). On the other hand, when there is only one line connected on a given busbar, as in the test system 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. Therefore, in such a topology, $C_{busbar}$ modeling is an important issue, even though it is sometimes disregarded.

Typical $C_{busbar}$ values may vary from 2000 pF to 0.1 $\mu$F Zhang et al. (2018); He (2016). Here, phase-to-ground stray capacitances of 0.1 $\mu$F were modeled at buses L and R in the test power system, following procedures reported in He (2016). Figs. 2 to 5 compare voltage and current signals obtained from a given solid phase A-to-ground fault at the middle of the line initiated at the voltage peak, considering the 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, but during the fault period, transients induced in voltage and current waveforms present significant differences, being more evident in current signals and less evident in voltages measurements when $C_{busbar}$ is taken into account. Indeed, when the busbar capacitance 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 abovementioned 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 phasors. In fact, even using 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 if traveling waves are required to be analyzed.

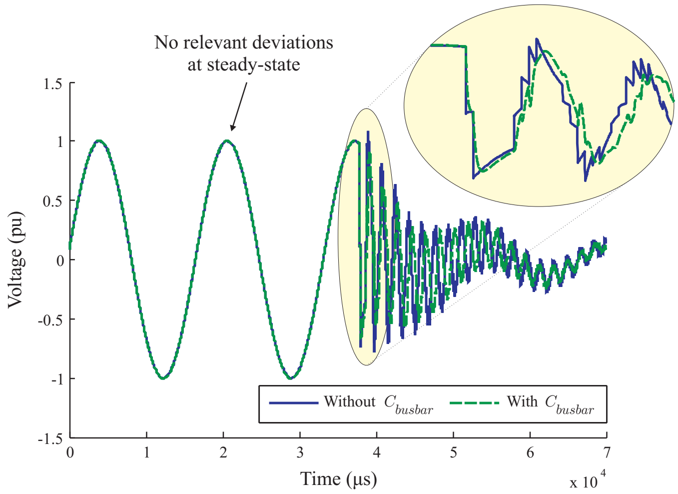


Figure 2. Local voltage signals with and without $C_{busbar}$.

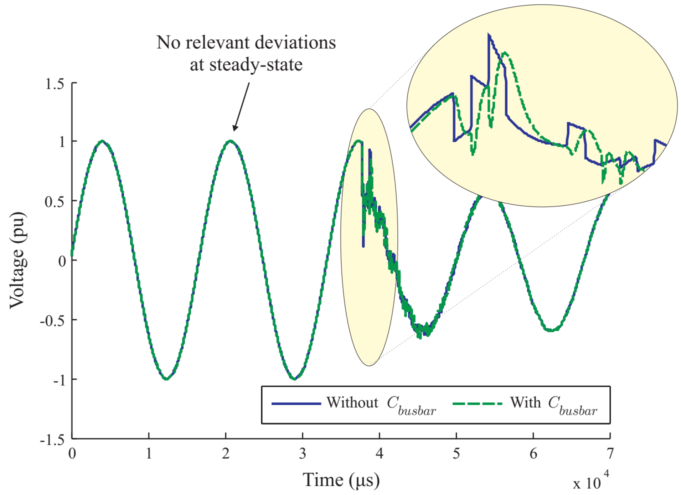


Figure 4. Remote voltage signals with and without $C_{busbar}$.

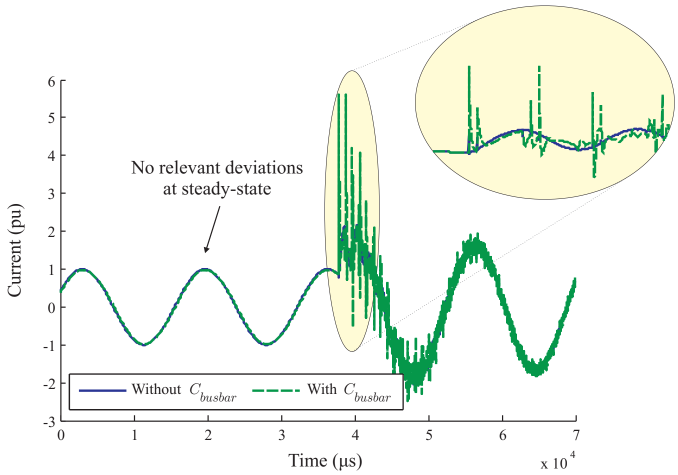


Figure 3. Local current signals with and without $C_{busbar}$.

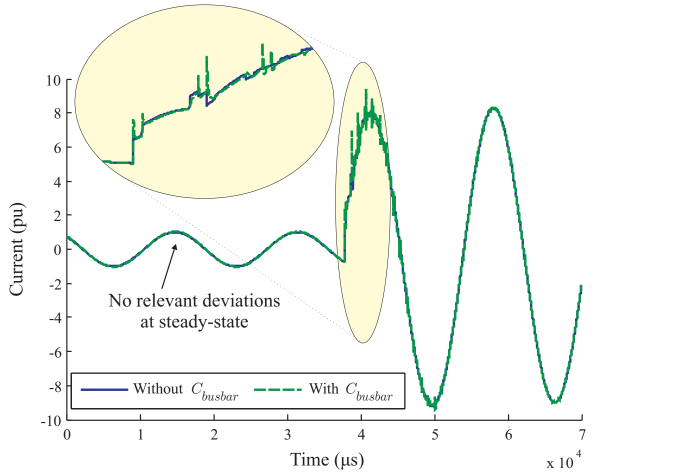


Figure 5. Remote current signals with and without $C_{busbar}$.

### *2.4 Relay Testing Procedures*

To test phasor- and time-domain-based relays, different test methodologies had to be used. 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 not need to represent transients in the order of hundreds of kilohertz. Thereby, the test set CE-7012 (Pereira et al., 2017) 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 (Guzmán et al., 2018). By using such a functionality, PS Simul generated records were directly loaded into the relay memory, being then played back, 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 a reliable analysis on the impact of $C_{busbar}$ could be performed.

## 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. Relays 1, 2 and 3 are equipped with phasor-based functions, whereas Relay 4 has time-domain high-speed functions, 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 lines that interconnect WPPs to the power grid. To evaluate these functions individually, pilot schemes were kept disabled. Besides, the communication between local and remote relays during the laboratory tests was accomplished by means of a short optical fiber, so that the channel latency effect was not analyzed in the obtained results.

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, fault inception angles $\theta$ equal to 0 and 90 degrees assuming a sinusoidal reference, 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 each protection function at both local and remote buses in the test system with and without $C_{busbar}$ were evaluated.

### *3.1 Number of Operation*

Figs. 6 and 7 present the number of operations of the 21 and 87 protection elements available in the evaluate relays. 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. 6, 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, not being 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. On the other hand, considering the time-domain Relay 4, the $C_{busbar}$ modeling showed to be a critical question, as no operation was verified when $C_{busbar}$ was disregarded. Indeed, as only one line is connected at both terminals, at the WPP side, traveling waves see a quasi open-circuit. It results in a negative reflection coefficient for current traveling waves (Greenwood, 1991), leading measured wavefronts to present high attenuation levels. As a consequence, the amplitudes of measured traveling waves are not enough to sensitize the time-domain differential element, restraining it at both line terminals 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 in the remaining 30% of simulated cases most are related to faults with $\theta$ close to 0 degrees, when traveling waves are not expected to be launched.

Analyzing Fig. 7, 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 time-domain distance element available in Relay 4 was observed. These results do not change significantly when $C_{busbar}$ modeling is taken into account, which in turn only slightly affected the number of operations of Relays 2, 3 and 4. A similar conclusion can be derived by analyzing the results obtained from Bus R. At this terminal, distance protection elements operated for a number of cases of about 60% of the simulated fault scenarios, which demonstrates that the relays underreached in some cases, since an 80% reach setting was used. However, from the point of view of the $C_{busbar}$ influence, the conclusion is that such a modeling issue was not critical for the 21 elements reliability, including the time-domain one. In this context, it is worthy to emphasize that the evaluated time-domain distance element is not based on traveling waves, but rather on instantaneous incremental quantities. Therefore, the Relay 4 eliminates frequency components much higher than few kilohertz, leading the $C_{busbar}$ modeling effects to be negligible. Also, the time-domain 21 element uses a directional supervision in its tripping logic, which becomes less sensitive for forward faults in weak terminals, as the WPP terminal in the test power system. Thereby, although the time-domain distance protection algorithm was sensitized in most cases, the directional supervision led the Relay 4 to restrain. Thus, in this case, the problem is not related to the $C_{busbar}$ modeling, but rather to the Bus L source strength.

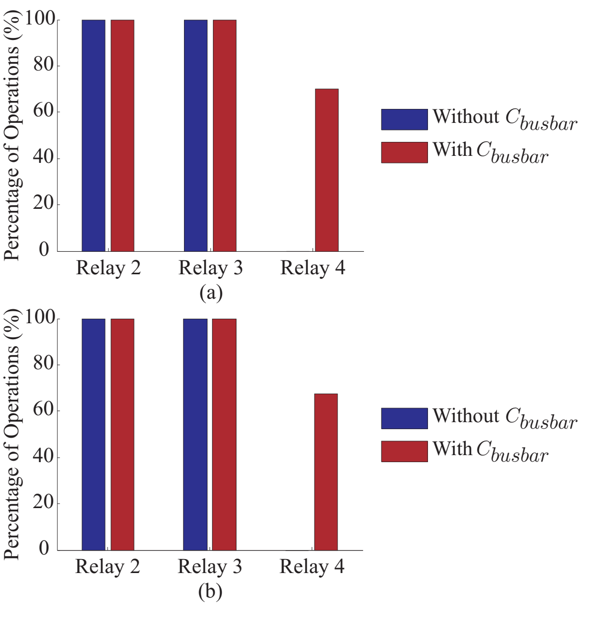


Figure 6. Number of differential element (87 function) operations at: (a) Bus L; (b) Bus R.

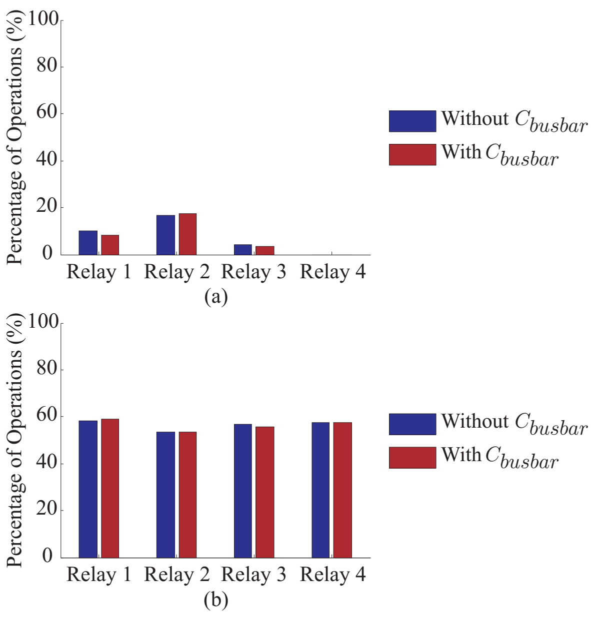


Figure 7. Number of distance element (21 function) operations at: (a) Bus L; (b) Bus R.

### 3.2 Operation Times

Figs. 8 to 11 illustrate boxplots that represent basic statistics of the operation times obtained from cases in which Relays 1, 2, 3 and 4 operated. 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. 8 and 9 show that the $C_{busbar}$ modeling is not critical for protection studies regarding the phasor-based 87 element, since the inclusion of $C_{busbar}$ resulted only in few different outliers in the boxplots of Relays 2 and 3. However, 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, as such function operated only when $C_{busbar}$ was taken into account. By analyzing Figs. 10 and 11, differences in the operation times of the 21 elements available in Relays 1, 2 and 3 were observed. Such differences were more relevant at the WPP side, being negligible at the remote line end. At Bus L, the maximum operation time of Relay 1 was reduced by few miliseconds when $C_{busbar}$ was taken into account. Regarding Relay 2, one can see that the maximum upper quartile increased from the order of 20 ms to 30 ms, making additional outliers to appear in between 30 ms and 35 ms when $C_{busbar}$ is not modeled. Besides, maximum operation times of Relay 3 increased from the order of 37 ms to approximately 50 ms at Bus L when $C_{busbar}$ was included in the PS Simul simulations. Finally, Relay 4 was not relevantly affected by the $C_{busbar}$ modeling, as it restrained in all cases at the WPP terminal (Bus L), presenting a very similar behavior at Bus R irrespective of the $C_{busbar}$ modeling.

The general conclusion is that the $C_{busbar}$ modeling affect the protection reliability, especially if transient-based functions are under investigation. Indeed, it can relevantly change the number of operations simply by including or not the $C_{busbar}$ in the used EMTP modeling, as in the case of the time-domain 87 element. Besides, from the point of view of operation times, the conclusion is that the $C_{busbar}$ modeling is more critical at the WPP side, where a weaker terminal is usually verified. In fact, at the power network side, no relevant differences were found in the evaluated relays operation times. However, at the WPP side, more evident differences were noticed, which reached the order of 5 to 10 ms in few simulated scenarios. These differences resulted sometimes in faster operations, but in other cases in slower operations, not presenting a well-defined relation between the $C_{busbar}$ modeling and the protection operation speed. Even so, the most important finding is that differences in relays operation may exist whether $C_{busbar}$ is modeled or not, which should be taken into consideration if the protection operation speed and reliability are under investigation.

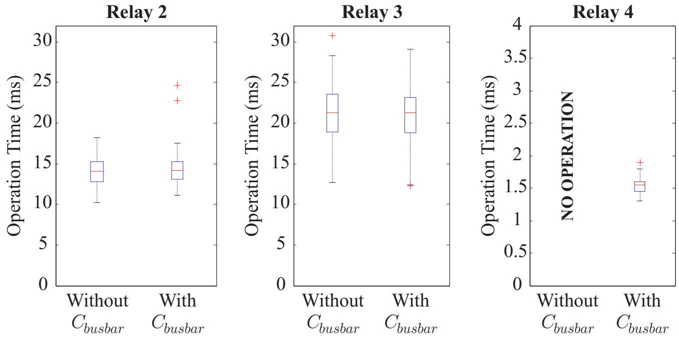


Figure 8. Boxplots of 87 protection function operation times at local terminal.

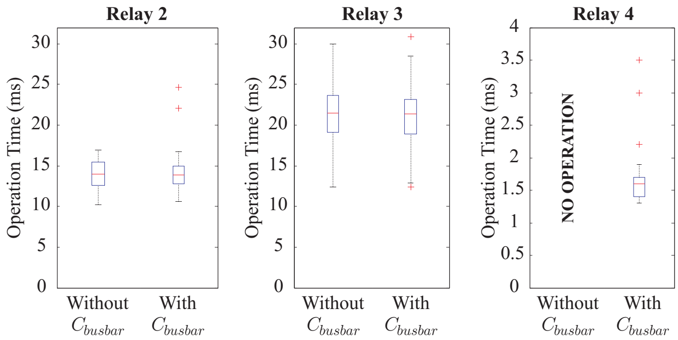


Figure 9. Boxplots of 87 protection function operation times at remote terminal.

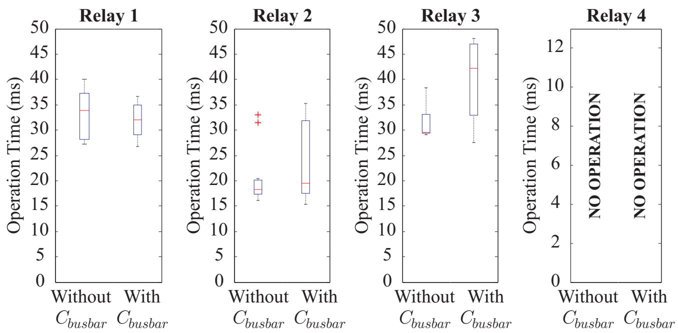


Figure 10. Boxplots of 21 protection function operation times at local terminal.

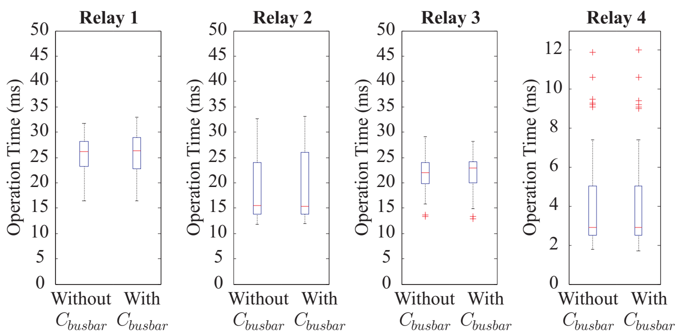


Figure 11. Boxplots of 21 protection function operation times at remote terminal.

## 4. CONCLUSIONS

This paper presents an analysis on the influence of the busbar capacitance modeling during protection device testing procedures in transmission lines that interconnect wind farms to the power grid. As the typical connection topology consists of series transformers and only one line connected at the monitored busbar, stray capacitances become an important modeling issue during relay testing procedures based on EMTP generated records.

To perform the proposed study, the PS Simul program was used to simulate faults on a typical wind power plant connection system. A 500 kV/60 Hz transmission line was taken into account, and Type 4 wind power generation units were considered. Four real protective devices 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 functions, including a traveling wave-based differential element, and an instantaneous incremental quantity-based distance protection element.

From the obtained results, the first conclusion is that the busbar capacitance modeling can be critical when transient-based protection functions are under investigation, especially at the wind power plant side where a very weak terminal is verified. Although voltage transients at the weak terminal tend to be stronger, current transients tend to be highly attenuated, jeopardizing the operation of current traveling wave-based functions as the tested time-domain 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 elements when the busbar capacitance is and is not taken into account, although the distance protection functions have shown to be compromised at the weak terminal. Indeed, as these functions mainly analyze signals within the inferior spectrum range, the busbar capacitance effect is not significant, leading the weak fault contribution at the wind power plant side to be the most critical issue. For instance, at the weak terminal side, phasor-based 21 elements did not operate in most cases, and although the time-domain 21 element was sensitized, its directional supervision restrained it, because it lost sensitivity due to the weak source, i.e., the problem was related to the source strength rather than to differences in transient patterns induced by busbar capacitances, as in the case of the 87 time-domain element.

Regarding the relays operation times, although no relevant differences were verified at the power grid side in cases in which the busbar capacitance was and was not modeled, at the wind power plant terminal, significant performance variations were observed. Operation times of phasor-based 87 elements were not significantly affected, but the analyzed 21 elements presented relevant differences comparing scenarios in which the busbar capacitance is and is not modeled. In this context, phasor-based 21 elements were more affected than the 21 time-domain element, resulting in operation time differences of the order of 10 ms. Thus, generally speaking, it is concluded that there is no direct relation between the busbar capacitance modeling and the protection operation times, but it was observed that differences in the operation times can exist, making the protection operation sometimes faster and sometimes slower, depending on the fault scenario. Hence, despite some variance in relays operation times that may exist due to the testing methodologies, the obtained results reveal that the busbar capacitance should be modeled in cases of weak terminals, as it occurs in wind farm connection busbars, especially if tests of transient-based functions are of interest. Otherwise, results can significantly affect the protection performance due to a modeling aspect, which must be avoided during relay testing procedures.


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