Importance of EMT-Type Simulations for Protection Studies in Power Systems with Inverter-Based Resources

Felipe V. Lopes *, *Senior Member, IEEE*, Moisés J. B. B. Davi †,
Mário Oleskovicz †, *Member, IEEE*, Giovanni B. Fabris ‡
Federal University of Paraíba (UFPB), João Pessoa, Brazil*
University of São Paulo (EESC-USP), São Carlos, Brazil†
Instituto Federal de Santa Catarina (IFSC), Santa Catarina, Brazil‡
Email: felipelopes@cear.ufpb.br*

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***Abstract*—This paper addresses the importance of Electromagnetic Transients (EMT)-type simulations for protection studies in power networks with inverter-based resources (IBRs). Firstly, real records taken from IBR interconnecting lines are analyzed to explain possible effects of transient events on phasor-based protection elements. Then, EMT-type simulations are carried out to demonstrate the impacts of IBRs on protection elements, which can be analyzed only via EMT programs (EMTP). Finally, since traveling wave (TW)-based solutions have been reported as promising alternatives to complement conventional protection schemes in the presence of IBRs, a list of system EMT modeling recommendations is presented to guarantee realistic TW studies in IBR interconnecting lines. The conclusions show that transient events in power systems with IBRs must be considered in protection studies, pointing out the importance of EMT-type simulations.**

***Keywords*—EMT-type simulations, IBR, phasors, protection, transmission lines, traveling waves.**

I. Introduction

The application of IBRs have been encouraged worldwide to decarbonize the electrical power grids. Among the existing IBRs, photovoltaic and wind turbine-based (types III and IV) power plants stand out. These generation units are often connected to the grid through a single transmission path, having electrical outputs synthesized in accordance to the inverter control strategies. Hence, IBRs usually result in weak fault contributions, which also present atypical features that can affect protection schemes [1], [2].

The need for reliable pre-operational relay testing platforms capable of correctly representing IBRs and their related impacts on protection schemes has been highlighted by various professionals. The literature is plenty of works reporting unstable behaviors of phasor-based protection elements during faults in systems with IBRs, mainly due to transient events [1], [2], [3]. Also in this context, TW-based solutions have been pointed out as promising approaches that can complement traditional phasor-domain protection. In this way, EMT-type simulations have gained importance in the context of protection studies for systems near IBRs. Indeed, they allow the evaluation of transient events, supporting the analysis of modern TW-based solutions.

High inertia systems were predominant for a long time, so that electrical quantities used to be well-behaved after the fault steady-state period is reached. In these systems, the frequency and angle reference of voltages and currents are mainly dictated by the system synchronous generators, which are features that can be properly represented by phasor-domain simulations during protection performance studies. Nevertheless, phasor-domain models are admittedly simplified [4], and with the increasing insertion of IBRs in the power grids, other transient events in addition to the fault-induced transients are taking place and causing variations in operating conditions during the fault period. Hence, depending on the transient event, phasor-domain models can be unrepresentative.

Despite the simulation aspects mentioned so far, there are still doubts about the reasons that could justify the use of EMTP for protection studies in power systems with IBRs rather than conventional phasor-domain short-circuit programs. Thus, this paper demonstrates transient events that can occur in the presence of IBRs, justifying the application of EMTP. Also, modeling aspects of power systems with IBRs that can influence phasor and TW-based technologies during relay testing procedures are highlighted, being EMTP modeling recommendations presented.

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II. Phasor-Domain *versus* EMT-Type Simulations

As reported in [4], EMTP are capable of simulating a wideband frequency spectrum by solving differential equations via numerical solutions. In this type of simulation, the use of small time-steps is required, guaranteeing high time resolutions, which must be sufficient to represent the highest frequency components of interest. However, it leads the simulation to be time consuming, making it difficult to initialize EMTP cases when several IBRs are considered in the same simulation scenario.

From the perspective of simulation models, EMTP allow detailed grid and control modeling, including the representation of Phase-Locked Loop (PLL) schemes and TWs launched by faults on the IBR interconnecting line. On the other hand, phasor-domain simulations focus on the fundamental frequency component only, such that large time steps can be used, significantly reducing the simulation computing time. Also, the system initialization is simpler than in EMTP. However, grid and control models (including the PLL model) are often oversimplified [4], which can result in an inaccurate representation of IBR behaviors under fault conditions. Obviously, the authors recognize that the use of EMTP does not necessarily mean that IBRs are accurately represented. Indeed, it depends on the considered level of modeling details. Hence, the use of complex models may be required to obtain realistic simulations, and it can pose difficulties to users, depending on their experience with EMT-type simulations. Even so, EMTP are the platforms that can provide the most realistic representation of IBRs under transient events, whose proper simulation is of utmost importance for protection performance studies in modern power grids.

To contextualize the importance of EMT-type simulations, real AG fault records obtained from an IBR interconnecting line in Brazil is depicted in Fig. 1. In this case, distance (mho element [5]) and differential (alpha plane element [6]) phasor-based protection functions operated as expected, issuing a tripping command in about 12.5 ms after the fault inception. As shown in Fig. 1, currents in all phases increase during the fault period, because they are dominated by the zero sequence current contribution from the grid [2], [3]. Even with the satisfactory operation, this case is useful to illustrate the trajectory of each protection element during the transition of phasors from pre-fault to a fault condition. Such a transition is often called ”phasor stabilization period” and it occurs due to the data window used by phasor estimation filters. Hence, the larger the data window, the longer the time period required to fill it with only fault samples, which cause a convergence delay in estimated phasors.

In addition to the phasor variations during the stabilization period, system transients can also occur, affecting the accuracy of estimated phasors. For instance, the DC decaying component is a well-known source of error [7]. Even so, the observation of fault steady-state phasor measurements is usually considered to start soon after the phasor filter data window completely enters the fault period [8]. Thereby, here, it is assumed that the fault steady-state can be observed about a power cycle after the fault inception, because one-cycle phasor estimation filters are applied.

Depending on the trajectories of protection elements during the system transition from pre-fault to fault conditions, protection performance issues can take place. However, if traditional phasor-domain simulation programs are used, only the samples in pink color shown in Fig. 1 would be available. As a result, studies on the impacts transient events in systems with IBRs during the fault period would be unfeasible.

In practice, most relays use phasor estimation filters that apply data windows with lengths equal to half or one power cycle. Thereby, it would be expected to observe stable system fault responses after the stabilization period. However, when IBRs are used, even after the transition period, IBRs can remain changing their operating conditions, yielding variations in electrical quantities which are difficult to predict.

To demonstrate the abovementioned issue, Fig. 2 shows another real AG fault case in an IBR interconnecting line installed in Brazil. The analyzed fault starts at about 163 ms, and the theoretical phasor stabilization period ends at about 180 ms, when phase and sequence current phasors tend to stabilize. However, at approximately 210 ms, magnitude and angle variations take place, even after the phasor stabilization period and before the opening maneuver of line circuit breakers. These variations can be associated to the IBR behavior, and they pose difficulties to define what is indeed the fault steady-state condition to be considered in protection studies. Thus, while these variations are difficult to be emulated via phasor-domain simulations, they can be represented in EMTP, provided that control schemes are properly modeled.

III. IBR-Associated Transient Events Which Can Affect Protection Functions

There is a variety of IBR-associated transient events that can affect protection functions. Among the most influenced algorithms, distance protection elements stand out, such that they are considered to demonstrate the protection performance issues analyzed in this paper.

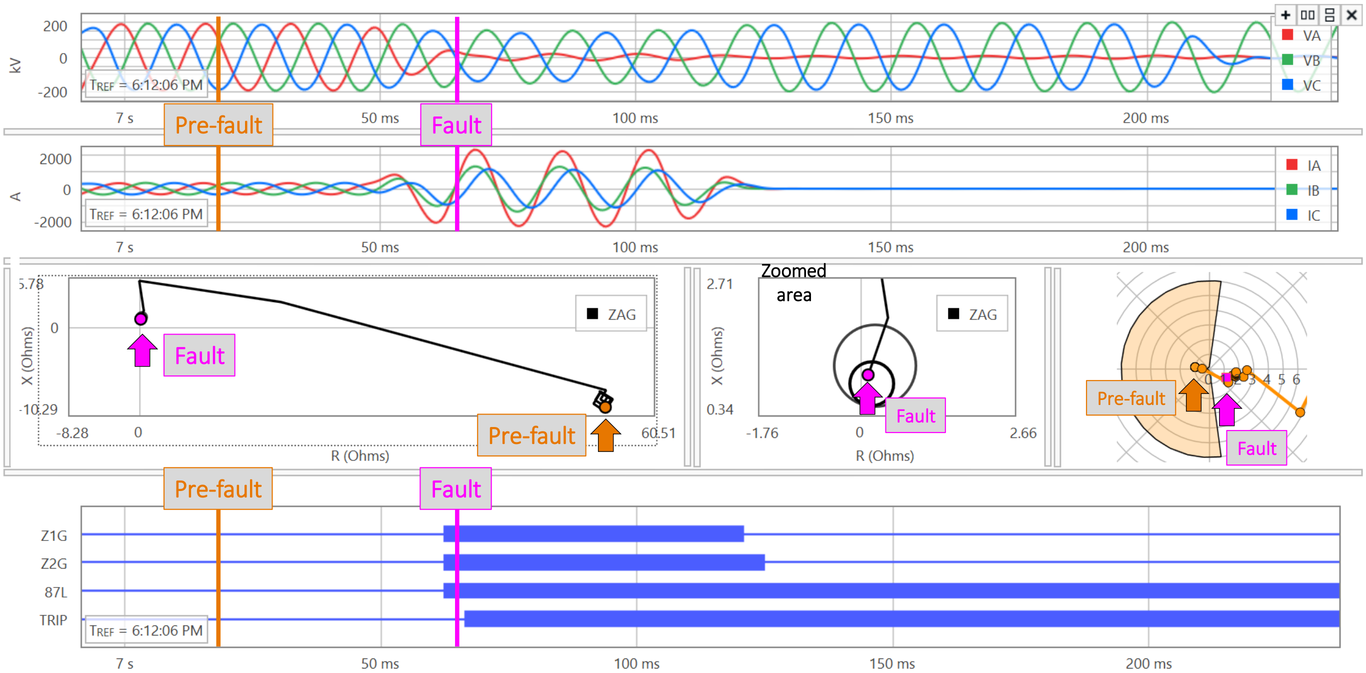

Figure 1: Real case to illustrate the protection behavior during the transition from pre-fault to fault condition.

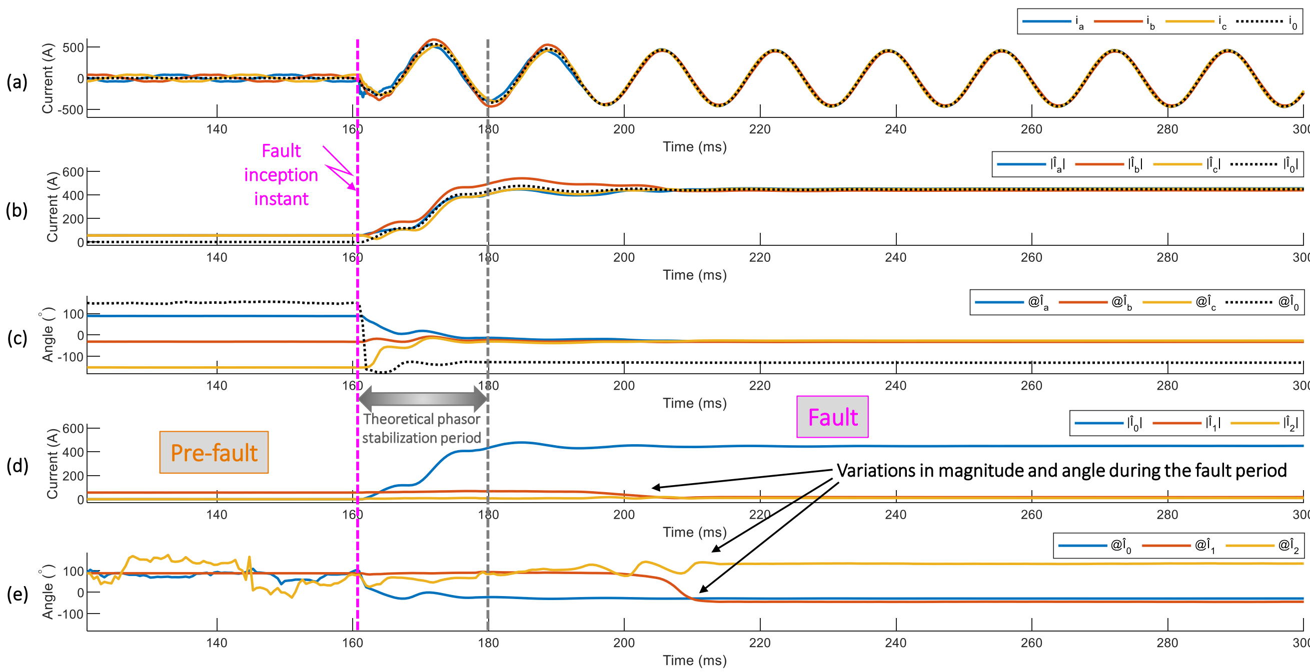

Figure 2: Real case to illustrate magnitude and angle variations that can take place even after the phasor stabilization period: (a) Current instantaneous values; (b) Phasor magnitudes of phase currents; (c) Phasor angles of phase currents; (d) Phasor magnitudes of sequence currents; (e) Phasor angles of sequence currents.

The first analyzed transient event is related to the IBR inverter power switching, which yields distortions in output signals. These distortions are not completely eliminated by IBR terminal filters and transformers [2], and thus, spurious frequencies may take place in monitored signals. As a consequence, the quality of phasor estimations can be jeopardized, consequently affecting the protection performance.

When the systems with IBRs are analyzed from the point of view of frequency variations during the fault period, understanding the PLL operation is key to explain some of the most challenging scenarios. In typical grid following IBRs, PLLs analyze voltages to obtain information about the grid frequency. Since IBRs are weak sources, relevant undervoltage is often observed at the connecting buses during faults (see Fig. 1). These low voltage levels lead PLLs to face difficulties during the system frequency estimation, which can in turn present errors. Therefore, IBR output currents are synthesized with frequencies different from the one at the grid side, causing frequency deviations that can significantly influence phasor-based protection [2]. Hence, by using grid codes which favors the voltage regulation over the system, frequency deviations in IBR output currents can be reduced, smoothing the impacts on protection elements [3].

Finally, it is important to mention that some transient events are not directly related to the IBR control strategy, but rather, to other elements that compose the generation unit. For instance, the crowbar circuit is used to protect converters applied in Doubly-Fed Induction Generators (DFIG). When the crowbar operates, it short-circuits the converter to protect it, leading the DFIG to operate as a typical induction generator. Thus, if a DFIG wind turbine is operating with high slips and the crowbar operates, the frequency of output currents can significantly deviate from the grid frequency [1], affecting the performance of phasor-based protection.

The mentioned events are transient in nature, and thus, they can be simulated only in EMTP. To demonstrate the reported transient events and the capabilities of EMT-type simulations to represent them, case studies are run considering the test system shown in Fig. 3 [3]. Faults at different points are tested and, although distance relays are assumed to be installed at both line terminals, only the local one is assessed here. To represent the IBR, a Full-Converter (FC) wind power plant (type IV) is firstly taken into account, which is put into operation according the European Grid Code (EGC) and American Grid Code (AGC) reported in [9], [10], [11]. For such initial scenario, the distance protection behavior is evaluated for faults at F2 and F4 (see Fig. 3), being the obtained responses compared against those verified when a conventional synchronous generation is considered. The results for such study are shown in Fig. 4. Then, in Fig. 5, an example of crowbar operation in a DFIG unit (type III) is presented, considering faults at F1, F2, F3 and F4. In all cases, the reactive/resistive reaching values for zones 1 and 2 are respectively set as 80%/130 Ω and 120%/200 Ω just for the sake of illustration.

It is noticed that the impedance seen by the relay presents a well-behaved trajectory when conventional synchronous generation is applied. Since the impedance rapidly converges to its steady-state point, phasor-domain simulations would be acceptable in this case. On the other hand, when IBRs are taken into account, the impedance trajectories are badly behaved, which can result in protection malfunction if the IBR is not quickly disconnected from the grid. Furthermore, as demonstrated, these trajectories depend on the fault position, grid codes, crowbar operation, and several other aspects, leading the protection performance to be difficult to predict during the fault period. Hence, since these transient events cannot be represented by phasor-domain simulations, the importance of EMTP studies is attested.

IV. TW-Based Protection and EMTP Modeling Recommendations

In the previous sections, the importance of EMT-type simulations for protection studies in power networks with IBRs was discussed. Major focus was given to phasor-based protection elements, proving that grid codes, crowbar and fault location can directly interfere in the IBR transient operation, affecting in different ways protection schemes. Aiming to overcome such issues, TW-based protection solutions have been reported as promising alternatives, mainly because they keep respecting the electromagnetism theory, even in the presence of IBRs. As a result, TW-based protection elements are gaining importance and popularity in the context of power grids with IBRs, making the use of EMTP mandatory for pre-operational protection testing procedures. However, when EMTP are used to represent TWs on IBR interconnecting lines, the used models must be detailed enough to guarantee representative simulations, otherwise, erroneous conclusions about the protection performance can be drawn. Therefore, this section lists important EMTP modeling aspects to be considered during the assessment of TW-based protection elements.

A. Frequency Dependence of Line Parameters

In [12], aerial and ground modes TWs are compared, considering simulated and real records obtained from a single-phase fault case. Such study also presents a comparison between transients obtained by using the Bergeron line model, which is frequency-independent (being typically set at the power frequency) and JMarti line model, which is frequency-dependent. The results show that representing line parameter frequency dependence is crucial to properly represent TWs, especially if both aerial and ground TWs are required to be analyzed.

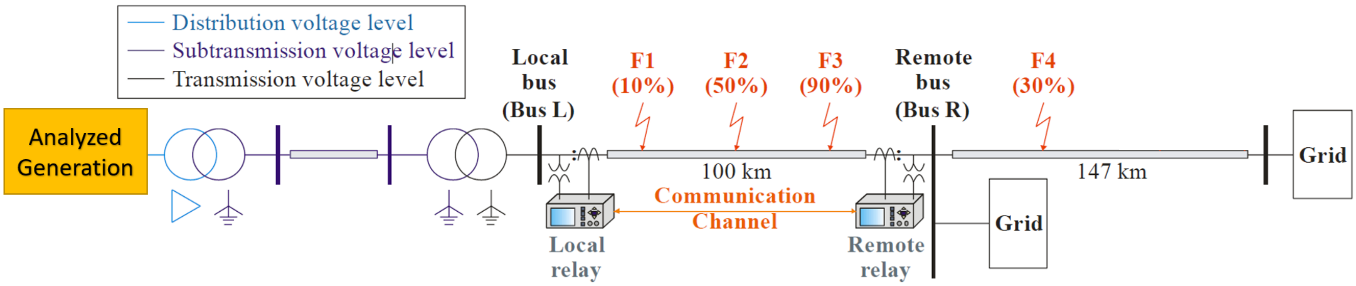

Figure 3: Test system used to evaluate transient events in power systems with IBRs.

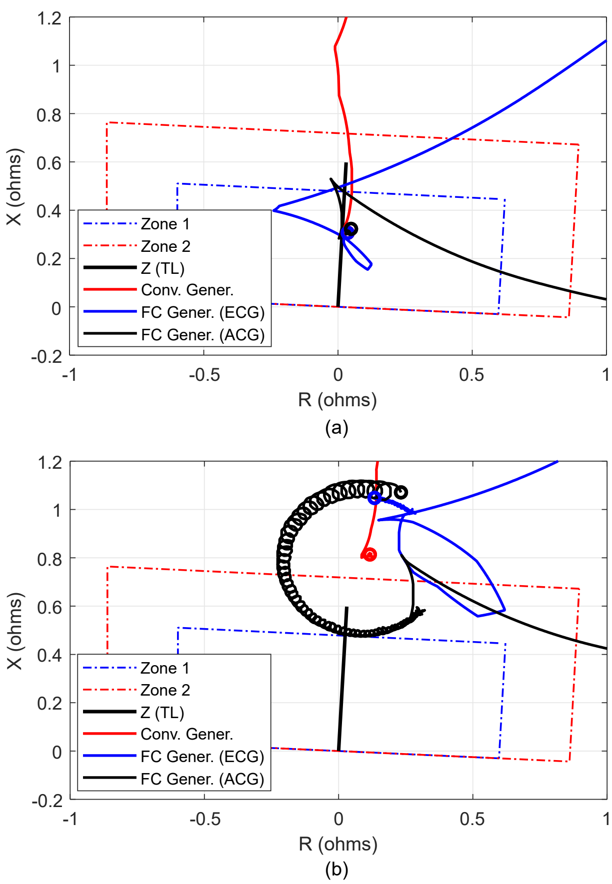

Figure 4: Distance protection behavior at local bus for different generation types and grid codes: (a) Fault at F2; (b) Fault at F4.

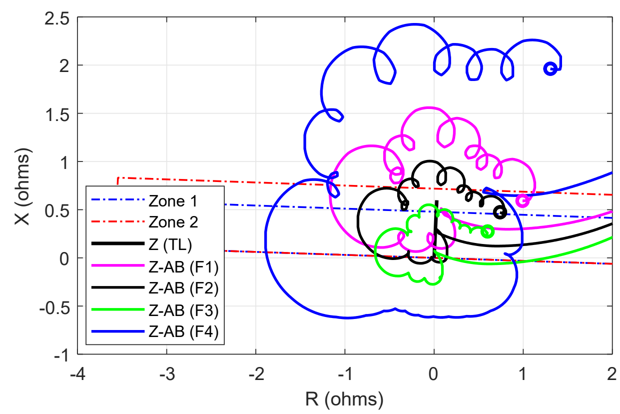

Figure 5: Distance protection behavior for faults at different locations, considering a DFIG wind power plant and the crowbar operation.

B. Earth resistivity uncertainties

Still in the context of TW-based applications, some relay manufacturers have patented solutions which consider the detection of ground mode TWs or even reflections from the fault [13]. Such type of solution can support one-terminal non-unit protection applications, which are very welcome for IBR interconnecting lines, especially if communication channels are lost, disabling differential and pilot protection elements [3].

Based on the presented considerations, it is concluded that the accurate modeling of earth resistivity is important, because it influences ground mode TWs and wavefronts reflected from the fault due to the mixing mode phenomenon. Indeed, as reported in [14], in grounded fault cases, ground and aerial modes are coupled at the fault point, leading ground mode TWs to generate aerial mode ones, and vice-versa. As a consequence, as the earth resistivity influences ground mode TWs, it can also influence aerial mode TWs generated from the mixing mode. Thereby, accurate earth modeling is also recommended, especially if ground mode wavefronts and aerial mode reflected/refracted TWs are required to be analyzed.

It should be pointed out that the earth resistivity is also an important aspect for phasor-based protection studies. Again, considering grounded fault cases, currents are dominated by zero sequence components [3], such as illustrated in Figs. 1 and 2. Thereby, the earth impedance can affect current levels that flow from the neutral connections of transformers to the line. Hence, a realistic modeling of earth resistivity is also recommended for phasor-based protection studies.

C. Line Termination Features

TWs measured at line ends are given by the superposition of incident and reflected TWs. Since the reflection coefficient depends on the line termination, they dictate the waveshapes [15]. In lines surrounded by other lines, the equivalent characteristic impedance of adjacent lines is typically considered during the determination of line termination features. Hence, the other connected equipment become less determinant in the reflection coefficient. However, for transformer-terminated lines, such as those typically used to connect IBRs to the grid, TW studies require busbar and/or transformer stray capacitances to be modeled, otherwise, simulated TW measurements become quite attenuated, being different from real ones [15]. Thus, a detailed termination representation is needed, especially for TW-based protection studies.

Another important aspect is related to the grid strength. In the cases presented in this paper, strong power grids were considered. However, in future power networks, with the increasing insertion of IBRs, the grid side can become weak and, depending on the system, dominated by inverters. Hence, future challenges are expected, because transient events will depend on the relative strengths of line terminals [2], [3]. Thus, the need for accurate modeling of line terminations can be extended to both line terminals, being also important for phasor-domain protections.

V. Conclusions

This paper highlights the importance of EMT-type simulations in the context of protection studies in power systems with IBRs. Firstly, real cases are presented to demonstrate transient events that can occur in the presence of IBRs during the fault period. Then, EMT-type simulations are carried out, illustrating the effects of fault location, grid codes and crowbar operation on the distance protection transient behavior.

The presented results attest that EMT-type simulations are essential for protection studies and developments in power grids with IBRs. Such conclusions apply to both traditional phasor-based protection elements and modern TW-based protection functions, which are gaining importance in the context of applications in power systems with IBRs. Indeed, there are IBR transient events which cannot be properly represented in phasor-domain simulation, especially those regarding the presence of non-fundamental components in monitored signals. It attests the importance of EMT-type simulations. Even so, EMTP models must be detailed enough to be representative. Hence, based on the authors experiences, a list of modeling recommendations was presented. Furthermore, it is recognized that EMTP studies result in computational challenges, and many platforms are devoid of standardized IBR models. Thus, contributions in EMTP platforms providing accurate open-source standardized IBR models are of utmost importance.

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