Differentiating between Applicability of Simulation Domains and Inverter Mathematical Models in these Domains

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Differentiating between Applicability of Simulation Domains and Inverter Mathematical Models in these Domains

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Abstract

Increase in inverter based resources in both the bulk power system and distribution system along with recent bulk power system events have triggered a debate in the industry with regard to the use of simulation domains for planning studies. This goes hand-in-hand with a discussion on the applicability of mathematical models in these simulation domains that are used to represent the behavior of IBRs. However, often the distinction between the applicability of a simulation domain and the applicability of a mathematical model in these simulation domains is overlooked. This article attempts to provide further insight, and showcase the importance of having to consider this distinction.

Index Terms

Electromagnetic transient, inverter based resources, positive sequence

I. Introduction

The increase in inverter based resources (IBRs) in transmission systems, along with recent disturbances in bulk power systems around the world, has brought to the forefront the need for accurate and validated mathematical models that represent the dynamic behavior of these power plants [1]. Additionally, these events have initiated an intense discussion regarding type and appropriateness of various simulation domains and IBR models used by planning and operations engineers at electric utility companies. The development and subsequent use of any mathematical model comes with an associated query of accuracy and more importantly, sufficiency, of the model's response in comparison to the response measured from actual equipment. However, it is not practical to expect that there can be one model that can span across multiple simulation domains. In fact, a hierarchy of models with varying levels of complexity and fidelity depending on the model's purpose is common across many disciplines. Therefore, it is important to identify the most appropriate simulation model to be used for the study to be conducted.

Until relatively recently, use of positive sequence simulation platforms has been the state-of-the-art for bulk power system planning studies around the world. Since IBR control algorithms are proprietary in nature, 'black box' or 'user-defined' simulation models are generally provided by the original equipment manufacturer (OEM) for studies in positive sequence. While these models do have the advantage of higher accuracy, there can be computational difficulties associated with the use of many of these models when studying a large system [2]. Hence, to facilitate conduction of planning studies with large numbers of IBR, under the aegis of the Western Electricity Coordinating Council (WECC) Modeling and Validation Subcommittee (MVS), a suite of generic IBR models have been developed and improved over time [2]. These models are structured in a way (as shown in [2]) that enables them to represent the trend of the dynamic response of inverters from many different IBR vendors.

Positive sequence simulation environments facilitate ease of conducting large interconnection wide planning studies. However, inherent limitations in the nature of the setup and conduction of positive sequence simulations may be restrictive while analyzing the impact of IBRs in the bulk power system. Although there are valid arguments that can be constructed with respect to limitations of positive sequence simulation environments and IBR models, these arguments should be carefully applied. All models in a particular simulation environment may not be equivalent. Further a given model in a particular simulation domain does not completely characterize the capabilities of the entire simulation domain. At the same time, parameterization of models in all simulation domains, is extremely important.

Regarding IBR models, a positive sequence simulation model does not necessarily imply that it is a bad or insufficient model while the mere presence/availability of a model in a detailed simulation domain (such as electromagnetic transient (EMT)) does not necessarily imply that the model is either a correct or an accurate model. A similar statement can be constructed for generic vendor agnostic models and OEM provided user defined models. This article will provide a perspective on the importance for differentiating between capability of a simulation domain and availability of sufficient models in these simulation domains.

II. Boundary between simulation domain capability and model capability

Recent bulk power system event analysis reports [3], [4] provide a detailed insight of various factors due to which IBRs have tripped for transmission system events. Through this analysis, the ability of positive sequence and EMT simulation models available to a transmission planner today to represent the various tripping behavior have been compared. This comparison highlights the inability of certain types of models in capturing various tripping conditions/scenarios. There can be few reasons which contribute towards the inability of a model to represent a given behavior. One reason can be a model with inappropriate or inaccurate parameterization of its parameters. Another reason can be a model which does not explicitly represent a particular behavioral characteristic of the device, such as not explicitly representing dc voltage dynamics in positive sequence domain, although it can be modeled. This is not necessarily a limitation of the simulation domain itself but can rather be an explicit model limitation. A third reason, which is more relevant for IBR plants, can be assumptions made to represent the collector network inside the plant as an equivalent circuit model.

It is recognized and acknowledged that the comparison in [3] is constructed on the basis of models that system planners have today and as a result, it can be fair to say that many causes of tripping cannot be captured in these models. This however does not reflect on the complete capability of a simulation domain to capture these causes of tripping and rather, the comparison captures the capability of the models provided in these simulation domains. This inference is specifically obtained as [3] mentions that although detailed EMT models were available, both positive sequence and EMT models that were available to the transmission planner were unable to showcase the tripping behavior observed during many events. Hence, while it is true that the presently available positive sequence models have limitations in representing these particular tripping behaviors, this doesn't automatically imply that the mere availability and use of EMT models is the solution. Nor does it imply that these tripping behavior cannot be represented in positive sequence simulation domain at all. The ability to represent tripping of IBRs in a simulation domain depends upon (as also highlighted in [3]),

1) use of the appropriate simulation domain,
2) having accurate and validated models of IBRs along with clear and explicit requirements that allow for procurement of models,
3) accurate representation of the power system network,
4) additional supplemental models (such as relay or collector network) to be represented,
5) simulation of the initiating event.

The first two points help to effectively highlight the nuanced difference between capability of a particular simulation domain and IBR models in that simulation domain. One can use a very detailed simulation domain but the study results can be inaccurate if adequate models are not used. At the same time, limitations showcased by an inadequate model in a particular simulation domain should not directly reflect as an inadequacy of the corresponding simulation domain.

In next section, using recent research results, the extent to which the capability of simulation domains *and* models can be leveraged is highlighted, *provided accurate, verified, and validated models* are used.

TABLE I: Capability of positive sequence and EMT simulation domains using accurate and validated models

Tripping reason	**Positive sequence domain**	**EMT domain**
	Representable in domain?	**Representable in domain?**
Erroneous frequency calculation	Yes	Yes
Instantaneous sub-cycle ac overvoltage	No	Yes
PLL loss of synchronism	Yes	Yes
Phase jump tripping	Yes	Yes
DC reverse current	Yes	Yes
DC low voltage	Yes	Yes
Instantaneous sub-cycle ac overcurrent	No	Yes
Instantaneous sub-cycle ac overvoltage—feeder protection	No	Yes
Measured underfrequency—feeder protection	Yes	Yes

III. Model improvements to fully utilize simulation domain capability

The objective of a mathematical model (in any simulation domain) is to provide system planners a reasonable view of how the system will behave. As a result, the evaluation of whether system planners can observe the causes of IBR tripping in their simulation studies is rightly driven by the models that they have presently. From multiple disturbance reports such as [3] it is apparent that the models presently provided to the system planners (both generic and user defined and in both positive sequence and EMT domain) have severe limitations, despite the presence of model validation standards and procedures. The necessary improvements and modifications of the models in EMT domain can adequately be carried out only by the OEM. However, with improvements in generic positive sequence simulation models, the capability of the simulation domains can be fully leveraged as shown in Table I. Along with this, improvements in model validation standards and procedures are also important.

It is intuitive that positive sequence simulation domains, which carry out simulations using root mean square (RMS) phasor quantities, will not be able to capture sub-cycle causes of tripping such as ac over voltage and over current. At the same time, although EMT simulation domains have the capability, many of the EMT models presently provided to system planners do not have this protection functionality represented. As a result, both in positive sequence domain (due to limitation of simulation domain) and in EMT domain (due to limitation of model provided), a transmission planner has been unable to observe these causes of tripping when conducting their studies. Here, the solution is to obtain improved and more accurate models in EMT domain. Additionally, a transmission planner may ask for a list of control/protection features that are not included in the model, along with reasons for their omission.

Regarding causes of tripping such as erroneous frequency calculation and PLL loss of synchronism, there have been recent improvements made to positive sequence IBR models [5] that have representation of a phase locked loop and inner current control loop dynamics. Further, these models operate at a lower simulation time step of 1ms as compared to a quarter cycle time step conventionally used in positive sequence simulations. Now, although [5] discusses the model implementation from a generic perspective, the model structure can be equally applied by OEMs in their user defined models. With such a structure, erroneous frequency evaluation and loss of synchronism can be captured to a certain extent in positive sequence simulations. Presently, most of the user defined black box positive sequence models provided by OEMs to transmission planners do not have representation of these faster control loops as it may have been assumed that positive sequence simulation domain does not have the capability to represent the impact of these fast control loops. Although this could be strictly true from a theoretical perspective, by applying suitable approximations (such as those applied in the REGC_C model) it can be possible for a transmission planner to at least obtain a visibility of the occurrence of an instability and subsequent trip. Hence here, the capability of the positive sequence simulation domain can be fully utilized through the use of improved models. Regarding black box EMT models provided to the transmission planner, although the EMT model should contain the representation of these fast control loops (PLL and inner current control loops), the models may not have had representation of the associated protection elements that react to signals generated by the PLL. As a result, here due to limitations of the models provided, a transmission planner has been unable to observe causes of tripping in their studies. In this scenario, both simulation domains have the necessary capability.

An example is shown in Fig. 1 and Fig. 2. Here, a PV plant is initially connected to a network with a short circuit ratio (SCR) of 4.0. At $t = 4.0s$, a fault occurs that takes the voltage down to around 0.6pu at the point of interconnection (POI) of the plant. Now in Fig. 1, the post fault SCR is 3.0 while in Fig. 2, the post fault SCR is 1.0. With a post fault SCR of 1.0, the PLL is unable to maintain synchronism (and erroneously evaluates frequency). There can also be situations wherein the PLL initially loses synchronism but is able to lock onto the the network voltage after one to two cycles. An example of such behavior taken from [5] is shown in Fig. 3. If an associated trip function is linked with this positive sequence model, then the tripping behavior can be captured. This comparison of the behavior of improved positive sequence models across both simulation domains showcases the capability that can be available from positive sequence domain. Here again, although capability can be available, it doesn't imply that system planners presently have sufficient models (in both domains). It is also noted that if the original causes of tripping are more related to the signal processing of the measured signals and transformation into their control variables rather than control system performance, then models in any simulation domain where signal processing techniques are not adequately captured, will not predict the resulting behavior. Here, it may be beneficial to standardize signal processing techniques across various generation sources.

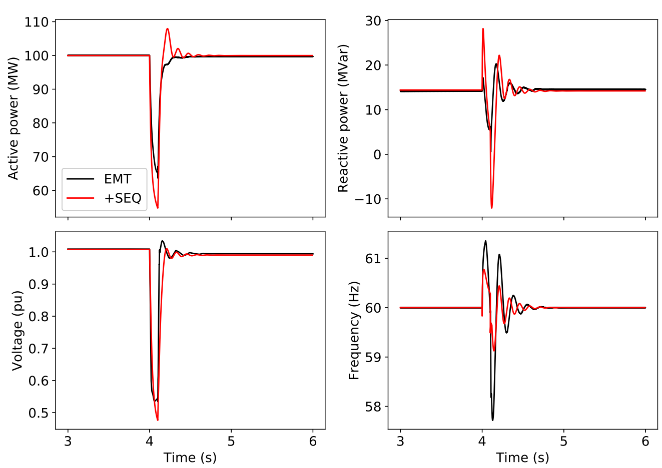

Fig. 1: Comparison of response of PV plant to a medium fault at POI with post fault SCR of 3.0

For scenarios where dc reverse current or dc low voltages were the cause of tripping, discussion of the capability of the models in simulation domains becomes further nuanced. Almost all positive sequence models of IBRs today do not represent

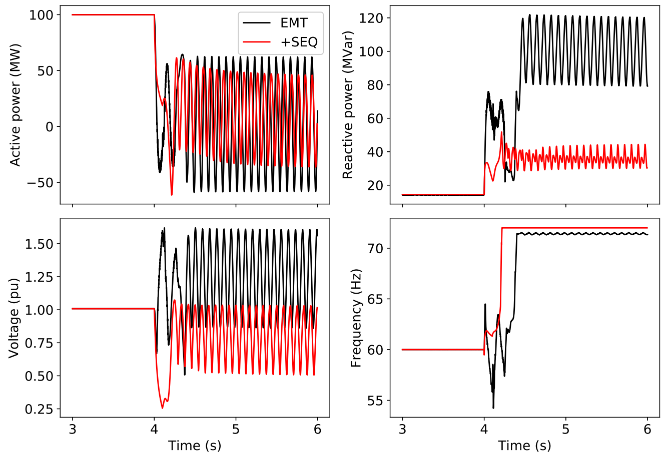

Fig. 2: Comparison of response of PV plant to a medium fault at POI with post fault SCR of 1.0

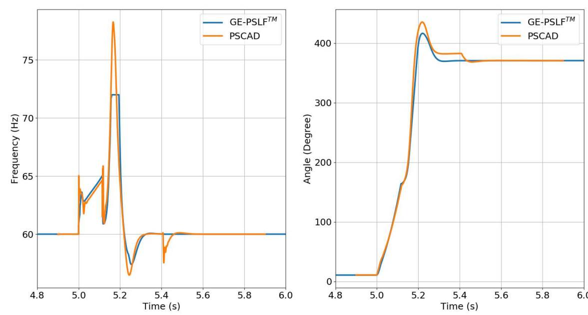

Fig. 3: Comparison of response of an IBR plant for an initial PLL loss of synchronism followed by subsequent synchronism one cycle later [5] (©2019 John Wiley and Sons. Reprinted, with permission, from John Wiley and Sons)

the dc side dynamic behavior. In fact, this is true even for some EMT domain models wherein an ideal dc voltage source is used on the dc bus. However, positive sequence domain does have the ability to represent low voltage or reverse current on the dc bus, if the representation of the IBR's dynamics is extended all the way to the source side. An example of such a model development is provided in [6] and example results are shown in Fig. 4 and Fig. 5. The control of the primary power source, the dc capacitor dynamics, and the inverter control all contribute to the dynamics of the dc voltage. Further, these can all be modeled in positive sequence transient stability simulators. But, while it can be possible to represent such behavior in positive sequence domain, it is unlikely that today transmission planners have models (even those provided by OEMs) that include this level of detail. Additionally, there is also an associated ambiguity on whether the EMT models provided to transmission planners can capture this behavior. It is recommended that further research and development be carried out on improving positive sequence models which can begin to include the dynamics of the dc side and source behind the inverter.

Finally, erroneously measured feeder/collector network level under-frequency protection can be represented accurately in both simulation domains, provided two conditions are met:

1) the feeder/collector network of the IBR plant is represented in detail in the corresponding simulation domain, and
2) the corresponding relay models are represented.

However, in present state of the art models provided to the transmission planner (both in positive sequence domain and in EMT domain), the feeder/collector network is not represented in detail and is instead represented by an equivalent circuit. As variation of frequency across the entire feeder/collector network is not expected to be diverse [8], it is possible to represent this form of tripping in an approximate manner in both simulation domains with use of the appropriate under-frequency relay models. However, the present models available to the transmission planner may not have the representation of the relay models. Increased research efforts are required to explore potential of adding the tripping behavior to models in all simulation domains.

Finally, to accurately capture the tripping of inverters due to sub-cycle over voltage and over current, detailed representation of the collector network may be required in EMT domain. This is because sub-cycle over voltage and over current are influenced by

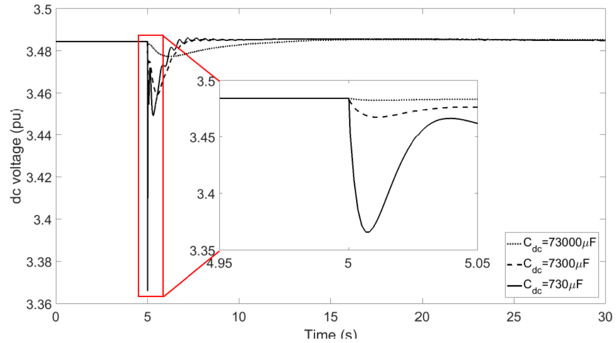

Fig. 4: Impact of dc capacitor size on variation of dc voltage of IBR resource for grid side event using a positive sequence model [7]

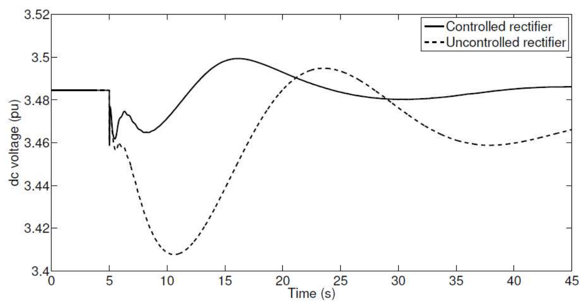

Fig. 5: Impact of rectifier control method on variation of dc voltage of IBR resource for grid side event using a positive sequence model [6] (©2018 IEEE. Reprinted, with permission, from IEEE)

the dynamics of the capacitor-inductor elements of the electrical network and such dynamics cannot be sufficiently approximated by an equivalent network.

To summarize, the capabilities of simulation domain versus the capabilities of models can be represented as shown in Table II. In these tables, the column on incorrect parameterization denotes that present models may already have the necessary features implemented, but their parameterization may not be accurate as compared to the parameterization in the field, and as a result the model is unable to predict the trip behavior. The column on representation within the model denotes the potential absence of necessary features within the model.

IV. Conclusion

This article highlights the importance of differentiating between capability of a simulation domain versus capability exhibited by IBR models in a particular simulation domain. Many a time, there can be limitations in the IBR models received by transmission planners which result in inaccurate simulation results. These limitations should however not be automatically construed to be a limitation of the simulation domain itself. Such a conclusion may draw attention away from a more pressing concern regarding the importance and need for accurate validation of all models in all simulation domains. The mere presence of a detailed model doesn’t naturally imply that the model is accurate. At the same time, the mere presence of a RMS phasor model doesn’t naturally imply an inaccurate model. The question should always be asked, are the models and the simulation platforms sufficient for the purpose of the study?

It should be noted that the intention of this article is not to suggest that EMT simulations are not important. With future large IBR penetrations, EMT studies will continue to hold importance. However, at the same time, it is important to recognize the extent of capabilities that can potentially be derived from positive sequence simulations with improved models. Computationally efficient simulators, such as positive sequence domain representations, will continue to be an important tool for the transmission planner to perform the vast number of sensitivities required to ensure the system’s stability. It is important to identify the sufficient mix of use of both simulation environments, with model accuracy and validity being rigorously verified equally across both simulation environments.

Considering many of the IBR disturbance reports indicate tripping of inverters for normally cleared faults remote from the inverter, it is unclear if the use of more detailed models by themselves would provide sufficient insight into this behavior, which is ultimately the purpose of modeling and planning studies. The increase in computational burden moving from phasor domain to EMT generally results in the reduction of the system for EMT studies. It is acknowledged that there are emerging

TABLE II: Summary of capability of simulation domain and sufficiency of models across both positive sequence and EMT domains to represent observed behavior of IBR during recent disturbances

a Positive sequence simulation domain

Cause of observed behavior	**Simulation domain limitation**	**Most of today's model incorrectly parameterized**	**Most of today's model do not represent**	
Unbalanced conditions	✓			
Sub-cycle ac over voltage	✓			
Sub-cycle ac over current	✓			
Momentary cessation		✓		Future model can represent as capability exists in simulation domain
Error in frequency measurement		✓		
PLL loss of synchronism		✓		
Collector network level underfrequency		✓		
Phase jump			✓	
dc reverse current			✓	
dc low voltage			✓	
Plant controller interactions			✓	

b EMT simulation domain

Cause of observed behavior	**Simulation domain limitation**	**Most of today's model incorrectly parameterized**	**Most of today's model do not represent**	
Unbalanced conditions		✓		Future model can represent as capability exists in simulation domain
Sub-cycle ac over voltage		✓		
Sub-cycle ac over current		✓		
Momentary cessation		✓		
Error in frequency measurement		✓		
PLL loss of synchronism		✓		
Collector network level underfrequency		✓		
Phase jump			✓	
dc reverse current			✓	
dc low voltage			✓	
Plant controller interactions			✓	

techniques that are looking into use of immense computational throughput to bring about EMT modeling of large scale grids. However, this results in a pure simulation based approach to analysis. Further, it may not be common to consider remote faults (many busses away from the IBR) in these analyses. The control of the inverter is proprietary, which limits the insight into the control for the system planner. The planner is not able to make global assumptions in the same way they can for analysis of the transient stability of synchronous machines (e.g., a close-in three-phase fault results in the maximum accelerating torque).

Future power system planning would require a combination of tools to be used either in a complementary manner or in a combined manner. It would be critical to identify use cases and scenarios that define the applicability of simulation environments. However, this should be with the use of verified and validated models in the simulation domain. A transmission planner should use the appropriate simulation domain for the task at hand and also ensure sufficient model validation and verification guidelines are in place.

V. Acknowledgments

The authors thank Dr. Ryan Quint of North American Electric Reliability Corporation (NERC) and Dr. Julia Matevosyan of Energy Systems Integration Group (ESIG) for their invaluable comments and suggestions that helped improve the narrative.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-EE0009019. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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