Validation of Power System Transient Stability Results

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***Abstract*— Simulation of the transient stability problem of a power system, which is the assessment of the short term angular and voltage stability of the system following a disturbance, is of vital importance. It is widely known in the industry that different transient stability packages can give substantially different results for the same (or at least similar) system models. Due to the usual lack of real-world data in the transient stability domain, in this paper we "validate" the software packages against each other. This is done by simulating the Western Electricity Coordinating Council (WECC) system models in three different widely-used software packages. Two specific approaches utilized to perform this validation are discussed. Also, the sources of discrepancies seen in the results from the different packages are investigated. This enables us to identify the differences in implementation of dynamic models in these different transient stability softwares, and also facilitates some improvements in these packages. In this process, we present certain example transient stability analyses of the WECC system models for different contingencies.**

Keywords- Power system stability; transient stability; validation; dynamic simulation; transient stability models.

I. INTRODUCTION

Power system transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on transmission facilities, loss of generation, or loss of a large load. The system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages and other system variables [1]. Fig. 1 represents the basic structure of the complete power system model used for transient stability analysis [1]. For some portions of the North American power grids, such as the Western Electricity Coordinating Council (WECC), transient stability has always been an important consideration [2], while for other portions it is of growing concern due partially to the widespread integration of wind generation.

Transient stability analyses form a critical part of assessing the system for security and planning purposes. It is, however, widely known that different industry-grade transient stability simulation tools can give substantially different results for similar system models, underlining the need for validating these results and the corresponding tools.

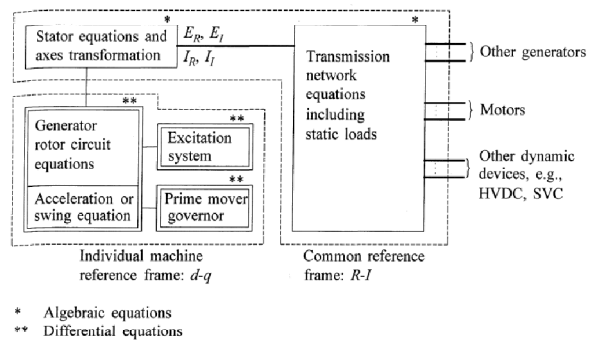

Figure 1. Structure of the complete power system model for transient stability analysis as depicted in [1]

Transient stability simulation packages are very large, complex pieces of software. As software undergoes a normal revision process, it is always possible bugs can be introduced. Similarly the system dynamic data is updated on occasion. If a user is only ever using one particular software package, it is likely this user would never be aware such bugs were introduced. The process outlined in this paper is a means for users to find and be aware of such bugs, and to thereby increase the confidence that both the simulation software and the system dynamic model is producing "reasonable" results.

References [3]-[7] address this issue and provide some comparisons between various dynamic model implementations for different transient stability software packages. We, however, know of no related work that provides comparisons using the WECC system. From the disparities in the results obtained from simulating the same system in different tools in [6], the authors conclude that validation of results obtained from different stability analysis tools with field experiments is crucial, as is the necessity of benchmarking and standardization of requirements for different simulation tools, thus warranting further research in this area.

Validation of simulation software is, "The process of determining the degree to which a model or simulation and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model" [8]. However, in the power system transient stability domain, there is usually a lack of real-world data to allow a direct comparison between simulation results and the real-world. Rather, in this paper, we simulate the WECC power system models using different, widely used commercial transient stability packages,

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and use them to "validate" each other. The main software packages used will be referred to as *Package A* (*PA*), *Package B* (*PB*) and *Package C* (*PC*).

The initialization of a transient stability simulation is based on the steady state network solution. Hence, in order to properly validate the transient stability solutions, it is important for the different packages to have power flow solutions that match, for the same system. With regard to the packages mentioned above, we correctly encountered a good agreement between them with respect to their static network solutions. Validating the transient stability results in the instances where the steady state network solutions don't match is beyond the scope of this study, since the emphasis is on the validation of dynamic models. As shown in Fig. 1, a transient stability simulation involves the solution of a set of differential algebraic equations associated with the dynamic models used to represent generators, loads etc., by the use of numerical integration techniques.

The remainder of this paper is structured as follows. Section II discusses the two approaches we developed to validate the different packages, with illustrative examples. Section III highlights some key differences in how certain models are implemented differently in the different simulation tools, with supporting examples. Section IV briefly describes the scope of future work in this validation effort. Summary and concluding remarks follow in Section V.

To ensure confidentiality of the WECC system data, alternative bus numbers, generator identifiers (IDs) etc. have been assigned in this paper, which do not reflect the actual numbers or names of any part of the system. Thus, any apparent vagueness about the system data is intentional.

II. Validation Methodology

As mentioned earlier, the goal of this work is to validate different transient stability softwares tools using the WECC system models. The sheer size of the WECC planning case, with around 17,000 buses, 3300 generators and 8200 loads, was one of the key challenges faced. To gage the complexity of the system, it should be noted that each generator can have a machine, exciter, governor, stabilizer and under/over excitation limiter model. Also, a sizeable number of loads have induction motor models. Hence the system has a total of 17,709 dynamic models. A WECC approved list of dynamic models is given in [9]. Moreover, individual dynamic models can have dozens of parameters that can substantially affect the behavior of the models. However, the problem is somewhat simplified by noting that the number of dynamic model types is substantially lesser than 17,709, with around 77 utilized in the WECC planning case.

In this work, two distinct methodologies have been developed to perform this validation, as discussed below.

A. Top-Down Approach

This method entails the simulation of the full 17,000 bus WECC case in different software packages. A contingency that causes significant movement in the system variables is applied. The idea here is to investigate the discrepancies observed in the results obtained from the different software packages, for such large system simulations, and track them down by identifying the sources underlying them. Typically, these discrepancies are caused by individual dynamic model (e.g. machine model) errors or "bugs", or by model implementation differences. In some cases, the discrepancies arise due to data errors and the associated auto-correction features in different packages. The latter is discussed further in Section III.

PA and *PB* provide a summary of the minimum and maximum values of all the state variables, at the end of a transient stability simulation. A comparison of these values of state variables obtained from different software packages provides a necessary condition for a match and helps in determining the sources of the larger discrepancies. This significantly enables narrowing down the focus to a particular part of the system and/or a model. In all dynamic simulations, the system is initially allowed to run unperturbed for about two seconds to demonstrate a stable initial condition ("no-disturbance run").

This example compares *PA* and *PB* for the full 17,000 bus WECC model. After the initial no-disturbance run, at time t = 2.0 seconds, two large generating units in the southern part of the WECC system were dropped and the simulation was run for 30 seconds. The time step used was 1/2 cycle which is approximately 0.00833 seconds. Bus frequencies and voltages were monitored at 20 locations to give a representation of system behavior. Fig. 2 shows the per unit (p.u.) voltage magnitude at the selected buses, in *PA*.

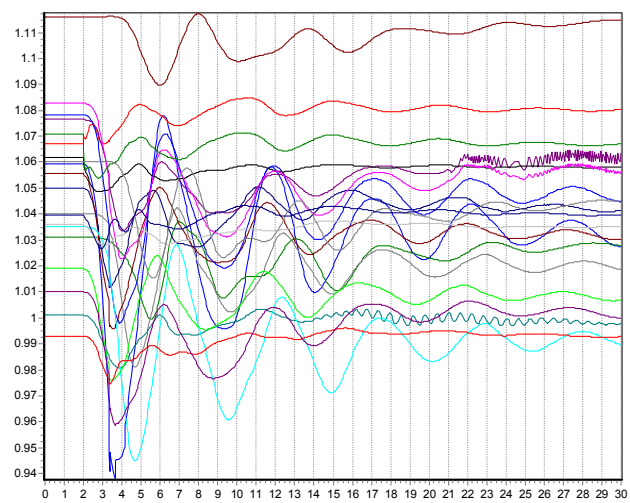

Figure 2. Per unit bus voltage magnitudes for 30 seconds of simulation in *PA*

Prominently visible in Fig. 2 is the oscillation at a particular bus, identified as Bus 11, starting at about 13 seconds into the simulation. This example details how this anomaly was used to help validate and improve *PA*. Given that this type of oscillation did not appear in any of the other voltage magnitude plots, it appears to be an isolated issue. The next step in the validation was to determine whether this oscillation also occurs in the *PB* results. Fig. 3 compares the voltage magnitude at this bus for the two simulations. Clearly, the results differ; moreover, the oscillation does not appear with *PB*. So the objective was to determine what is causing the oscillation in *PA*.

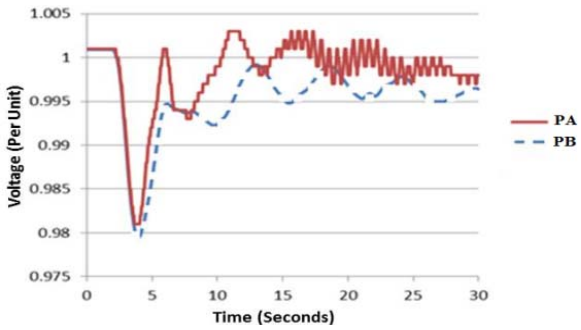

Figure 3. Bus 11 voltage maginitude comparsion between *PA* and *PB*

Since Bus 11 is a high voltage bus with no generation, the cause of the oscillations is not likely to be at that bus. One approach to tracking down the source of the oscillations is to study the first (immediate) neighbor buses to observe which have larger or smaller oscillations. Figs. 4 and 5 show the results at the first neighbor buses. The oscillation appears to be in the direction of Bus 12, which is joined to Bus 11 through three low impedance branches, and not in the direction of the other branch, which has a relatively higher impedance. The process is in turn repeated for the neighbors of Bus 12, with the highest shown in Fig. 6 for Bus 15. Repeating one last time results in the identification of likely sources of the oscillations - two near identical generators at Buses 16 and 17 (the voltage at Bus 16 is shown in Fig. 7).

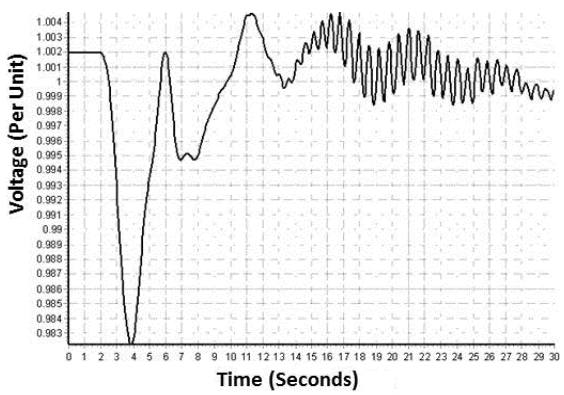

Figure 4. Bus 12 (first neighbor) voltage magnitude in *PA*

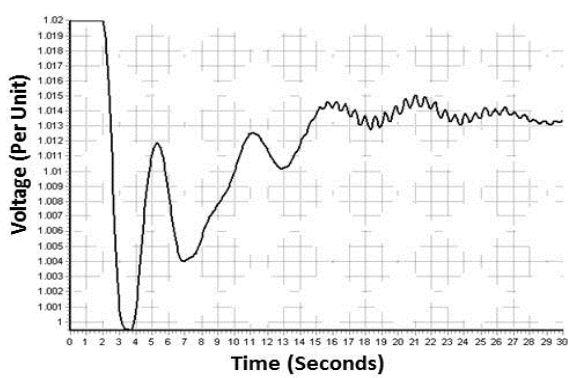

Figure 5. Bus 14 (first neighbor) voltage magnitude in *PA*

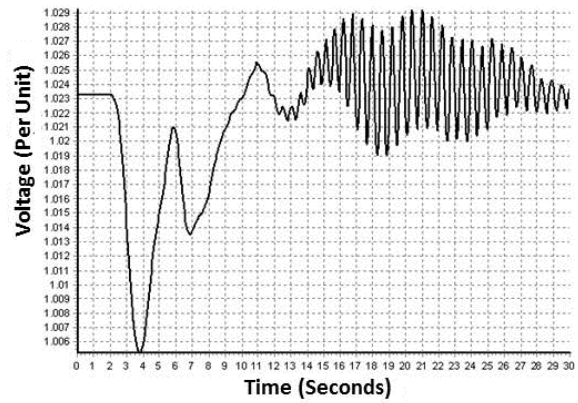

Figure 6. Bus 15 (second neighbor) voltage magnitude in *PA*

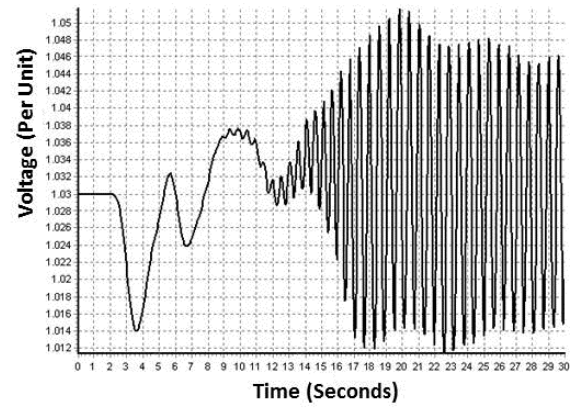

Figure 7. Bus 16 voltage magnitude in *PA*

An alternative process is to utilize the single machine infinite bus (SMIB) eigenvalue analysis process to see if there are any generators with positive eigenvalues in the vicinity of Bus 11. For this example, this process worked quite quickly since there were only two generators in the same area as Bus 11 with positive eigenvalues, at Buses 16 and 17.

Regardless of the process, after the problem generator(s) have been identified, the next step is to determine the reason for the unexpected behavior. A useful approach is to create a two-bus equivalent based on Ward network reduction techniques [10], consisting of the desired generator supplying an infinite bus through its driving point impedance, termed as the SMIB equivalent. The infinite bus voltage is set to match the initial power flow conditions. The dynamic models for the desired generator are retained, and those in the reduced portion of the system are eliminated. *PA* allows us to automate the process of creating such an equivalent. Once the SMIB equivalent is created, a balanced three phase fault is placed on the terminals of the generator at time t = 1.0 seconds for 3 cycles to perturb the system. This provides an initial assessment of the stability of the generator, and probably a confirmation of the eigenvalue results. Fig. 8 shows the generator's field voltage for this scenario. Clearly, the generator is not stable. This result also helps to validate the eigenvalue analysis since the unstable eigenvalue had a damped frequency of 1.86 Hz, very close to that in Fig. 8.

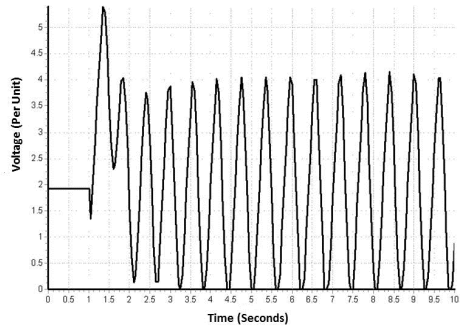

Figure 8. Generator 16 field voltage for two-bus equivalent fault scenario in *PA*

The next step is to determine whether the reason for the unstable results is an input data issue or is associated with how the generator's models are represented in *PA*. This process is facilitated by working with an SMIB equivalent, as opposed to the broader WECC case. Disabling the stabilizer gives a stable result for field voltage as in Fig. 9, indicating that the issue is probably with the stabilizer model.

Determining the exact cause of the instability is then a trial and error process, primarily achieved through modifying parameters to assess which ones have the most impact on the result. Another useful step is to verify that the parameters in the two-bus model match those in the *PB* dynamic data file. These values might be different because of (a) an error with the input process or, (b) modification by the "auto correction" during the model validation process that automatically occurs before the case is simulated.

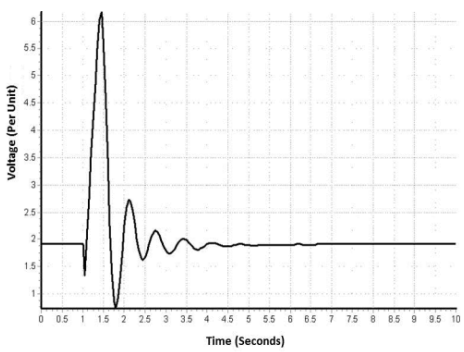

Figure 9. Generator 16 field voltage for two bus equivalent fault scenario with stabilizer disabled, in *PA*

For this example, the problem was actually due to too "aggressive" auto correction of the power system stabilizer (PSS) parameters. The generators at Buses 16 and 17 use dual-input type PSS models. These models consist of certain lead-lag blocks. For numerical stability reasons, as is common with other transient stability packages, *PA* was "auto-correcting" the denominator terms in the lead-lag blocks if the values were less than 4 times the simulation time step, and one of them was being set to 0. This led to the bypassing of a lead-lag block which caused the instability of the generators.

Using the SMIB equivalent, the original values for these denominator terms were restored and tested. This gives the stable result as shown in Fig. 10.

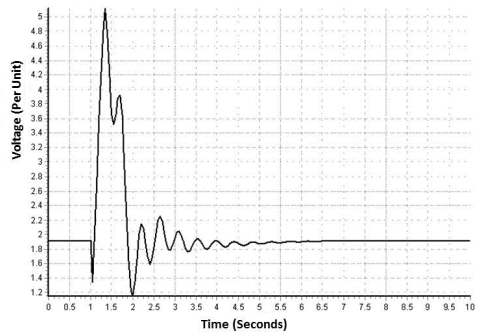

Figure 10. Generator 16 field voltage with stabilizer parameters returned to original values in *PA*

Consequently, the validation code for all the stabilizers in *PA* was modified to be less aggressive. In cases in which the lead-lag denominator time constants were small, multirate integration techniques are used. Given that the WECC case has more than 1000 stabilizers, this change affected 1226 separate parameter values, allowing the entered values to be retained. The results of the 30 second simulation for the full WECC Case with these changes are shown in Fig. 11. We notice that the oscillations at Bus 11 that were starting at t = 13 seconds, are now gone.

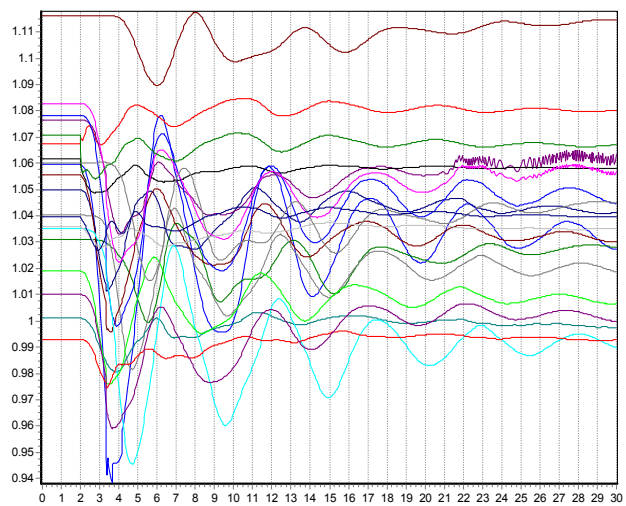

Figure 11. Corrected per unit bus voltage magnitudes for 30 seconds of simulation in *PA*

Thus, this example highlights the significance of tracking down the cause of discrepancies between results obtained from different packages for the full 17,000 bus case, by analyzing SMIB equivalents to focus on individual dynamic models.

B. Bottom-Up Approach

Of the 17,709 dynamic models in 77 different types in the WECC system, the 20 most common types account for 90 % of the models. These are the focus areas for this validation approach. It comprises of creating SMIB equivalents for the most common generator-side models which are then subjected to some contingency at the generator bus to test the individual models, across *PA*, *PB* and *PC*. Validating these commonly used models considerably impacts system-wide results. This

approach has also led to significant improvements in some of the packages we used for our analyses.

The round rotor generator model with quadratic saturation (GENROU) and the salient pole generator model with quadratic saturation on the direct axis (GENSAL), account for two-thirds of all the machine models in WECC. This approach is illustrated with an example of a GENSAL generator.

An SMIB equivalent was created at Bus 21, Generator 1, from the full WECC case. In addition to the machine model, the generator also has a Basler DECS exciter model called AC8B [9], commonly used in the WECC system. A solid three-phase balanced fault was applied at t = 1 second at this bus, which was self-cleared in 0.05 seconds. Thereafter, the response is shown for 10 seconds. A time step of ½ cycle was used. The preliminary comparisons between the results obtained from *PA* and *PC* are shown in Figs. 12 and 13.

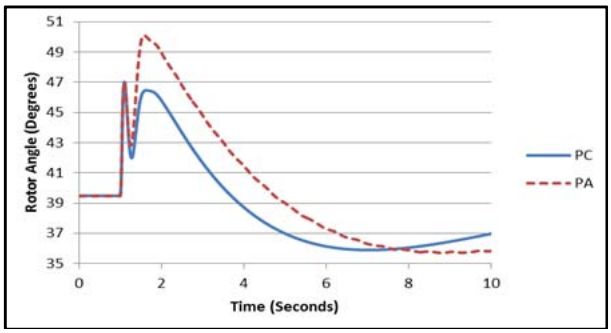

Figure 12. Comparison of rotor angles for the SMIB equivalent of Generator 1, Bus 21

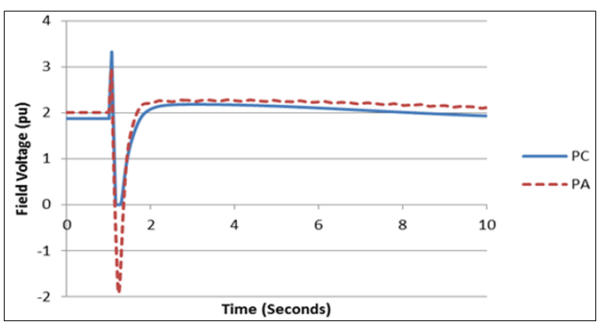

Figure 13. Comparison of field voltage for the SMIB equivalent of Generator 1, Bus 21

From an initial assessment, it is not apparent whether the issue lies in the machine model, or the exciter, or both. An important aspect of this methodology is to break down the problem to the individual components to check for discrepancies and then add these components back until the problem is encountered again. Therefore, we repeated this comparison with the exciter model disabled. The results are shown in Figs. 14 and 15.

By disabling the exciter we were able to determine that there were inherent issues in the GENSAL model. From Fig. 15, it is clear that the initialization of the field voltages is discrepant. After some investigation by *PA* developers into their code, it was found that there was an error in the way the generator saturation was fed as an input to the generator field current. Details about synchronous machines and their saturation modeling for transient stability studies are given in [11][12]. After corrections to the *PA* code, the field voltage initializations agreed with each other, as shown in Fig. 16.

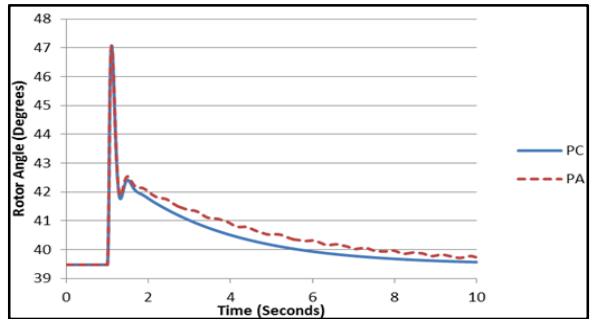

Figure 14. Comparison of rotor angles for the SMIB equivalent of Generator 1, Bus 21 with the exciter disabled

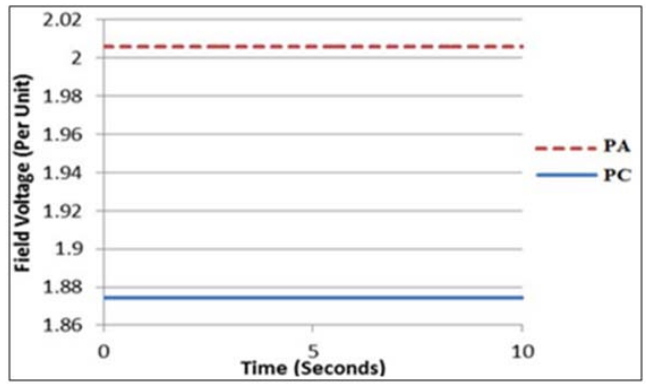

Figure 15. Comparison of field voltages and for the SMIB equivalent of Generator 1, Bus 21 with the exciter disabled

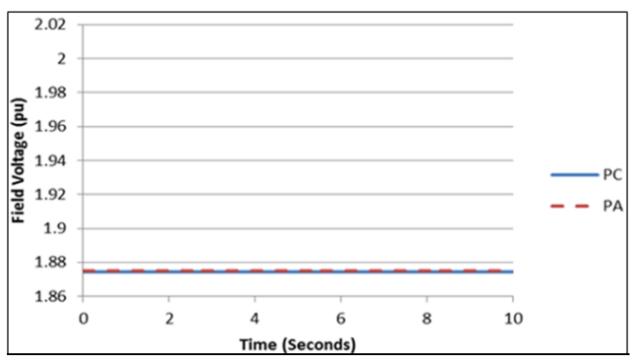

Figure 16. "Corrected" comparison of field voltages for the SMIB equivalent of Generator 1, Bus 21 with the exciter disabled

After the validation of the GENSAL model, the exciter model was enabled again. The same simulation was performed to check for any issues with the exciter model. Referring to Fig. 17, the issue was found to be due to the fact that *PA* was not enforcing the lower limit of 0 in the integration process to calculate the field voltage. Fig. 18 shows how the revised results from a subsequent version of the *PA* software, which incorporated the corrections in its GENSAL and ESAC8B model implementations, are validated against the *PC* results.

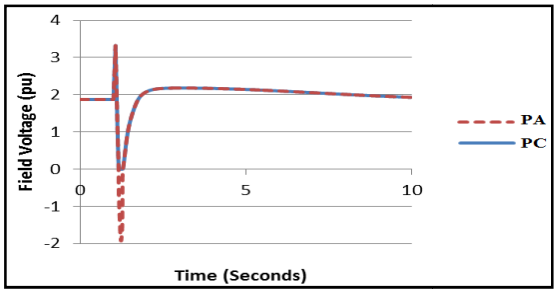

Figure 17. Comparison of EFD values with the exciter enabled

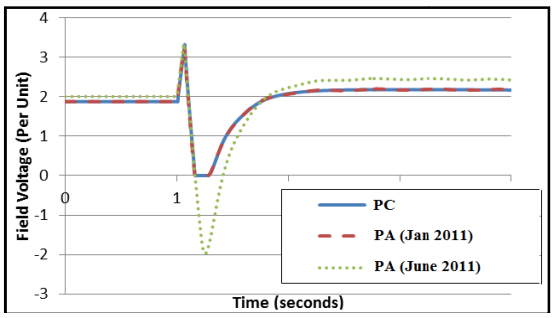

Figure 18. Comparison of field voltage values of SMIB case at Bus 21, Generator 1 between different versions of *PA,* and *PC*

In this study, a simple SMIB case with a machine and exciter model was used to illustrate this method. Typically, a generator can have a turbine governor, stabilizer and other control models and depending on their sheer number or impact on system response, it might be additionally necessary to validate those models. From our experience, this approach of validating the most commonly used dynamic models with the help of SMIB equivalents leads to significant reductions in the discrepancies between the results obtained from different softwares, even on the full WECC case scale.

III. Differences in Model Implementation

The previous section described two distinct approaches used to validate different transient stability simulation tools. In that process, certain "bugs" in some softwares were identified and reported. They were addressed in the subsequent software releases. However, we also found certain key differences in the way different softwares implement the same model. In these cases, a particular software's model cannot be deemed "incorrect" but is considered to be a software nuance, which normally stems from certain specific customer requirements. It was found that some of these implementation differences had a significant impact on results. Awareness of these differences in implementation has aided our validation studies. A few examples are discussed below.

A. Generator Saturation

Magnetic saturation affects the mutual and leakage inductances within a machine. To model this effect, saturation functions are defined for machine models. It was found that the packages use slightly different functions to model the saturation, which impacts the results. In this example, we used the simulation results of the generation-drop contingency for the full WECC case, that was described in Section II-A. While comparing the generator field voltages, it was noted that sometimes the *PC* and *PB* models gave slightly different results, which were large enough to require investigation. This was due to a difference in implementations of generator saturation for the GENSAL and GENROU models. Both models use a quadratic function in which the amount of saturation is inputted at p.u. fluxes of 1.0 and 1.2 (denoted as S_1 and $S_{1.2}$ respectively). For the GENSAL model, the saturation is a function of the direct-axis transient flux, whereas for the GENROU model it is a function of the total sub-transient flux.

From our analysis, the saturation function used in *PC* appears to be,

$$S(input) = B_{PC}(input - A_{PC})^2/input \tag{1}$$

We denote this as the scaled quadratic approach. Based on further numeric testing, the saturation function in *PB* appears to be,

$$S(input) = B_{PB}(input - A_{PB})^2 \tag{2}$$

We denote this as the quadratic approach. Since both curves are fit to the same points (1,*S*[1.0]) and (1.2,*S*[1.2]), the *A* and *B* coefficients are different, as are the *S*(*input*) values for inputs other than 1.0 and 1.2. *PA* implements both models, with an option of specifying which model to use.

As an example, the generator at Bus 29 of the WECC case is represented using a GENSAL model with *S*(1.0) = 0.1710 and *S*(1.2) = 0.9010. Curve fitting of the points gives the following equations for the scaled quadratic approach and quadratic approach respectively:

$$S(input) = \frac{9.8057(input - 0.8679)^2}{input} \tag{3}$$

$$S(input) = 7.1741(input - 0.8456)^2 \tag{4}$$

Fig. 19 shows the difference between the two saturation curves for varying levels of flux.

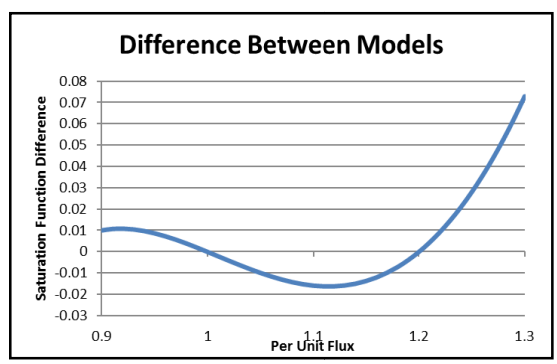

Figure 19. Comparison of difference in saturation between *PC* and *PB* functions

It is apparent that the difference is non-zero, except at the points $x = 1$ and $x = 1.2$. The difference in the saturation values for fluxes other than 1.0 and 1.2 p.u. results in differences in field voltage and subsequently in the values of the exciter state variables. For this example corresponding to Bus 29, in which the initial p.u. flux is 1.051, the scaled quadratic method gives an initial field voltage of 2.5137 p.u. (based on results using a two bus equivalent in *PC*) while the quadratic function gives a

value of 2.5034 p.u. (based on results from the full WECC case run in *PB*). Notably, the -0.0103 difference is close to that from Fig. 19. The initial field voltage is 2.5147 p.u. in *PA* when solved with the scaled quadratic saturation modeling and 2.5036 p.u. when solved with the quadratic approach, with both values closely matching those from the other two programs.

Since *PA* implements both approaches, the importance of the issue can be studied. In the WECC system there are 2533 generators with active generator models. The largest difference in the initial field voltage between the two saturation models is 0.0339 p.u. (at the generator at Bus 31), with only 23 generators having differences above 0.02 p.u. In terms of percentages, the largest difference is 1.66% at Bus 31, with 25 generators having differences above 1.0%.

This issue is thus not considered significant for our study system, but it needs to be considered during validation between the different packages, since differences in the field voltages can get amplified into differences in the initial exciter values.

B. Exciter Saturation

Magnetic saturation is also modeled for some excitation systems. Similar to machine models, the existence of three different exciter saturation functions was found in the process of validating excitation system models, as listed in Table 1.

TABLE I. TYPES OF SATURATION FUNCTIONS MODELED IN DIFFERENT PACKAGES FOR EXCITATION SYSTEMS

Type of saturation model	Function	Software
Quadratic	$S(x) = B*(x - A)^2$	*PB*
Scaled Quadratic	$S(x) = B*(x - A)^2/x$	*PC*
Exponential	$S(x) = B*\exp(Ax)$	*BPA IPF*

Initially, *PA* was following the convention of saturation modeling used in the Interactive PowerFlow software (IPF) developed by Bonneville Power Administration (BPA). However, from our benchmarking studies, we identified two other methods used in *PB* and *PC*. These options have been added to *PA* to aid the validation process with other packages. Fig. 20 shows the field voltage response of a generator in an SMIB equivalent. A balanced self-clearing fault was applied for 3 cycles to perturb the system.

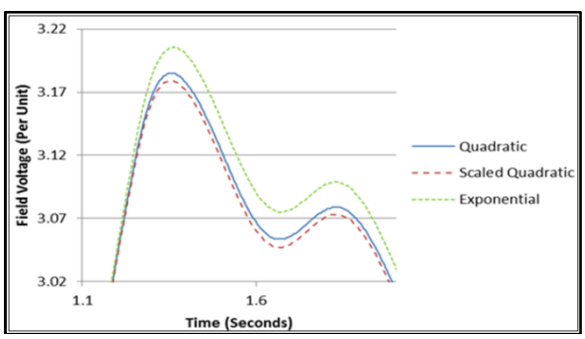

Figure 20. Zoomed in plot of a generator field voltage response for the exciter modeled with different saturation functions

C. Dealing With Data Errors and Auto-Correction

While performing studies on the WECC system, some errors in the dynamic data were encountered. The "known" errors are "auto-corrected" but how this is done is software specific. For example, in the WECC case data we found that for some generators, the stator leakage reactance X_l was more than the sub-transient direct or quadrature axis reactance, X_{dpp} or X_{qpp}. Clearly, this is not physically possible for a synchronous machine model, as explained in Equation 4.41 of [1]. *PA* treats this as an error and auto-corrects these values; but other software packages do not. In Section II-A, it was also noted how aggressive auto-correction of stabilizer model data was causing discrepancies. The "unknown" data errors as well as the different auto-correction procedures in different packages can stress the system in unusual ways, exacerbating model differences.

D. Turbine Load Controller Model

This example discusses a particular supervisory turbine load controller model that is used in conjunction with governor models. It changes the governor setpoint. The output of this control block is a proportional integral (PI) control. While trying to determine the reason underlying the differences in some governor outputs between *PA* and *PB*, we learned that for certain governors models, the output is scaled by a factor of 25 by the load controller model in *PB*. This greatly increases the action of the device, changing the system frequency recovery. From our testing, we observe that *PC* does not include this term, as shown in Fig. 21. The contingency mentioned in Section II-A was applied here. *PA* was modified to model both these approaches. This important finding from our Top-Down analysis enabled us to eliminate some large discrepancies in bus frequencies between *PA* and *PB*.

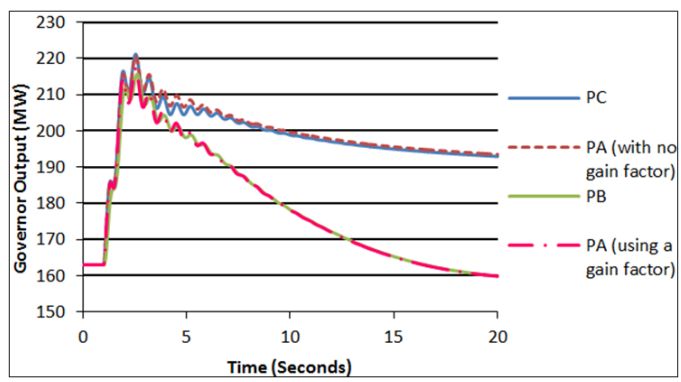

Figure 21. Comparison of governor output in MW for a particular generator with different implementations of the LCFB1 model

E. Speed Dependence of Certain Field Voltages

After applying the loss of generation contingency for the full WECC case as mentioned in Section II-A, the field voltage values initially decreased, such as for the generator at Bus 36. Further studies revealed that this is due to exciter field voltage output being multiplied by the generator speed. This operation was found in *PB* for some exciters, but not in *PC*. The exciter at this generator bus was found to be the IEEE type DC1 exciter. The IEEE standard for excitation systems doesn't have the speed dependence term modeled for this type of exciter [13]. *PA* had this speed effect modeled for a few, select

exciters. Fig. 22 shows the impact on field voltages at Bus 36 (with a type DC1 exciter) after some changes to the *PA* code for this model. The initial dip in the field voltage is caused by declining generator frequency.

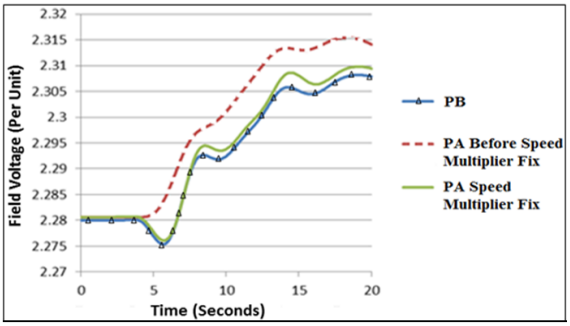

Figure 22. Comparison between the fiels voltage response of a generator with and without the speed multiplier

IV. FUTURE WORK

The effort to validate different transient stability software packages is ongoing. In order to handle practical planning models of the size of WECC, emphasis is being given on automating the dynamic simulation runs. Based on our experience with equivalents, we are working on an algorithm to dynamically create equivalents of different sizes such that the equivalents provide a good representation of the general large system behavior, thus aiding our validation studies. In this paper, we presented our analyses of the generator models. Loads also have dynamic models such as induction motor models, and these are in the process of being validated. Given the research thrust on increasing renewable penetration in the power grid, a logical future step would also be to validate the emerging wind and solar dynamic models. The challenge lies in the ultimate validation of softwares with actual field measurements obtained from phasor measurement units (PMUs), digital fault recorders (DFRs) and other sensing devices.

V. CONCLUSION

We have presented and implemented a preliminary methodology to validate transient stability software packages and models. Some key differences in dynamic model implementations in different softwares are also illustrated. Although we focused on the generator and its associated models, our methodology is scalable and can be used on systems of various sizes and for different types of dynamic models such as load models. We discuss the significance of running full system simulations with the Top-Down approach as well as the benefits of working with smaller sized two-bus cases with the Bottom-Up approach. From the existing literature as well as our studies, we can conclude that there is a pressing need for some kind of benchmarking or standardization of different power system simulation tools. Considering the multitude of critical operational and planning activities conducted on the grid using these tools, validating them needs to be a continuous and evolving effort.

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