ColumbiaGrid Power System Model Validation Process

NERC Reliability Standard MOD-033-1

Draft Version 1

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Introductions

The NERC MOD-033-1 Steady-State and Dynamic System Model Validation Standard is a reliability standard to establish consistent validation requirements to facilitate the collection of accurate data and building of planning models to analyze the reliability of the interconnected transmission system. The standard becomes effective on July 1st, 2017. It requires each Planning Coordinator to implement a documented process to perform model validation within its planning area. The process shall include the following 4 attributes:

- Comparison of the performance of the PC's portion of the existing system in a planning power flow model to actual system behavior;
- Comparison of the performance of the PC's portion of the existing system in a planning dynamic model to actual system response;
- Guidelines that the PC will use to determine unacceptable differences in the evaluated performances for the planning power flow and dynamic model;
- Guidelines that the PC will use to resolve unacceptable differences in the evaluated performances for the planning power flow and dynamic model.

ColumbiaGrid, in collaboration with its members and participants, develops this process document to satisfy the requirements aforementioned. It provides basic information on how ColumbiaGrid and its members plan to perform each tasks related to the power flow and dynamic validation, which criteria are to be used to determine the unacceptable discrepancy, and how to resolve the unacceptable differences.

Under the NERC MOD-033-1 requirements, validation of the planning power flow and dynamic models are to be performed at least once every 24 months. The process document serves as the proposed guideline for the repetitive validation efforts and subject to further modifications along the process.

1. Requirements and Measurements for Power Flow and Dynamic Validation in MOD-033 standard

Section B of the MOD-033-1 lists 2 requirements (R1 and R2) and their measurements (M1 and M2).

1.1 Requirement R1

For Requirement R1, the MOD-033-1 includes the following four sub-requirements for long-term planning:

1.1.1 Validation of the power flow model (R1.1.1)

It is required that the PC provides a comparison of the performance of the PC's portion of the existing electric transmission system in a power flow model to the actual system performance recorded data. The power flow model is either represented by a state estimator power flow case or by modeling real-time data information to off-line power flow model. The power flow model examination and comparison of the planning to real-time data should be performed at least once every 24 calendar months.

ColumbiaGrid will perform power flow model validation at least once every 24 calendar months with each participated PC (ColumbiaGrid members and participants), starting from 7/1/2017. It may include two types of validation options:

- Comparison of Power Flow Models with a notable event
- Examination of Power Flow Model during a peaking condition

For the first task, ColumbiaGrid and PC members will review and select notable events in its PC area or a WECC wide event. A notable event may include an event that affects: (a) a large part of the Western Interconnection; (b) a large part or all of the PC areas. A power flow base case will be created or adjusted to match the pre-fault conditions. This case may be converted from the Peak RC's west wide System Model (WSM) data if available, or created by ColumbiaGrid and its members by matching the status and outputs of modeled generators, status of transmission facilities, as well as modeled loads (real and reactive) to the actual system recorded data. The post-fault system conditions such as power flow will be compared to the state estimator data. The validated power flow cases may be used as the starting case for R.1.1.2 requirement dynamic model validation. The procedures details on event selection, base case preparation, etc. are discussed in section 4.

For the second task, ColumbiaGrid and PC members will review and determine the system peak condition for summer and/or winter, jointly collect data including state estimator data, system topology and device status, and create a power flow case to reflect the peak conditions. A notable event is not required for this type of peaking condition power flow model validation.

The primary MOD-033-1 power flow model validation work performed by ColumbiaGrid will be based on task 1. Task 2, if performed, can serves as additional model data validation efforts to understand the system model in peaking condition.

1.1.2 Validation of the dynamic model (R1.1.2)

It is required that the PC provide a comparison of the performance of the Planning Coordinator's portion of the existing system in a planning dynamic model to actual system response, through simulation of a dynamic local event, at least once every 24 calendar months (use a dynamic local event that occurs within 24 calendar months of the last dynamic local event used in comparison, and complete each comparison within 24 calendar months of the dynamic local event). If no dynamic local event occurs within the 24 calendar months, use the next dynamic local event that occurs;

ColumbiaGrid can perform dynamic model validation at least once every 24 calendar months with each participated PC (ColumbiaGrid members and participants), starting from 7/1/2017. ColumbiaGrid and participated members will review and select notable events in their PC areas or a WECC wide event with adequate real-time data.

In selecting an event, if Peak RC also includes the same event for its west wide system model power flow and dynamic data preparation, participated PC members will request the Peak RC for the actual system recorded data related to the event and authorize ColumbiaGrid to use it for model validation purpose. If the actual recorded data is not available from Peak RC, ColumbiaGrid may work with its members to request the event's relevant recorded data for dynamic model validation of the electric system within the PC Areas from involved transmission owners and operators. Participated planning coordinator, with the involvement of ColumbiaGrid, will work with the transmission owner, transmission planners, as well as generator owners to investigate and resolve the unacceptable differences from the simulated results and the actual system performance due to specific transmission or generator models (see Requirement R1.1.3). The procedures details on event selection, base case preparation, etc. are discussed in section 4.

1.1.3 Guidelines to determine unacceptable differences in performance (R1.1.3):

The standard requires the PC to develop and utilize guidelines to determine unacceptable differences in performance between off-line study models and actual system performance for Requirement R1's 1.1 and 1.2.

ColumbiaGrid and its members and participants have developed guidelines to determine unacceptable differences in performance between off-line study models and actual system performance to meet Requirement R1's 1.1 and 1.2. These guidelines are provided and discussed in further details in Section 5.

1.1.4 Guidelines for Resolving Unacceptable Differences (R1.1.4)

The PC shall develop and utilize guidelines for resolving the unacceptable differences in performance identified in Requirement R1's 1.3.

ColumbiaGrid and its members and participants develop and provide some general guidelines for resolving unacceptable differences in performance identified in Requirement R1's 1.3 in Section 6. In recognizing that models and real-time data discrepancy may be induced from various sources, ColumbiaGrid will review together with its PC members, with the possible assistance from Peak RC, transmission owners, generation owners, transmission operators and software vendors, the potential modeling concerns. The recorded data from the energy management system (EMS) and the phasor measurement units (PMUs) may be introduced to aid in isolating and investigating the discrepancies.

1.2 Measurement M1

Each PC shall provide evidence of having a documented validation process for meeting Requirement R1, as well as providing evidence of demonstrating implementation of the Requirement R1 components.

ColumbiaGrid and its members and participants prepared this document discussing its validation process for meeting Requirement R1. In addition, ColumbiaGrid will document the evidence of demonstrating implementation of Requirements R1.1.1 through R1.1.4. This will be discussed in further details in Section 3.

1.3 Requirement R2

Each Reliability Coordinator and Transmission Operator shall provide documentation containing actual system performance data to any PC performing model validation within 30 calendar days of a written request. The provided data can be in the form of, but not limited to, state estimator data or power flow case, or other real-time data, including PMU data and/or disturbance data recordings.

After selecting the notable events for power flow and/or dynamic model validation, participated planning coordinator members will request Peak RC for actual system performance data as needed in its validation process work. After obtaining the data and cases, ColumbiaGrid members will authorize ColumbiaGrid to use them for model validation purpose. If such data are not available from Peak RC, ColumbiaGrid may work with its members to request the event's relevant recorded data for transmission operators.

1.4 Measurement M2

Each Reliability Coordinator and Transmission Operator shall provide evidence, such as email notices or postal receipts showing recipient and date that it has distributed the requested data or written response that it does not have the data, to any Planning Coordinator performing validation under Requirement R1 within 30 days of a written request in accordance with Requirement R2; or a statement by the Reliability Coordinator or Transmission Operator that it has not received notification regarding data necessary for validation by any Planning Coordinator.

With M2, Peak RC and the transmission operators shall provide evidence, such as email notices and responses of providing the requested data (i.e., state estimator, real-time EMS and/or PMU data recordings, sequence of events, etc.) to the ColumbiaGrid PC members. If such a request has not yet been brought upon by the PC members at the end of the two-year compliance period, the Peak RC and/or the transmission operators also need to provide a statement, which can be in the form of an email to the ColumbiaGrid members, that they have not received a request from the PCs.

2. Retention of Evidence

To meet the MOD-033 standard's retention of evidence requirement, ColumbiaGrid and participated PC will keep data or evidence to show compliance with Requirements R1 through R2, and Measures M1 through M2, since the last audit, unless directed by its Compliance Enforcement Authority (NERC or WECC) to retain specific evidence for a longer period of time as part of an investigation.

If a participated PC is found non-compliant, it shall keep information related to non-compliance issue(s) until mitigation is completed and approved by the Compliance Enforcement Authority, or for the time specified above, whichever is longer.

3. Procedures for Validation of Power Flow and Dynamic Data

During the course of developing this procedure document, a number of documents have been reviewed by ColumbiaGrid and its members as the references. Basically, these are the criteria and procedures that were developed and adopted by regional organizations and neighboring entity. These documents are:

- NERC “Procedures for Validation of Power Flow and Dynamic Cases” (NERC procedure)[1]
- WECC “Guidelines for Validation of Power Flow and Dynamic Cases for MOD-033-1” (WECC guideline) [2]
- California ISO “Power System Model Validation Process” (CAISO process)[3]

The Procedures include event selection, data acquisition, data review, event review, base case development, comparison of power flow and dynamic model to the real-time data, and mitigation of model discrepancies. Guidelines for determining unacceptable differences of study models versus real-time data, as well as processes to resolve unacceptable differences, are discussed in the next two sections.

3.1 Event Selection and MOD 33 Study Work Group Formation

For both power flow model validation (the first option) and dynamic model validation, a notable event needs to be selected before the system response are validated. In particular, accurate dynamic model validation should be based on well validated power flow models. By this means, a preliminary step for each dynamic model validation can be the effort also satisfying the power flow model validation requirements of MOD-033. Therefore, a notable event, if available, should be selected for both power flow and dynamic model validation every 24 months.

WECC guideline suggests to use large disturbance events within Western Interconnection for model validation purpose. These type of events and corresponding impacts are practically observed and recorded widely within the Western Interconnection. In NERC MOD-033 background description, it clarify that a dynamic local event for model validation could be a subset of a larger disturbance involving large areas of the grid. Examples of these large disturbance are loss of PDCI and associated generation tripping, loss of both Palo Verde nuclear units, Chief Joseph braking test, etc.

As large system event occurs irregularly and unplanned, not all power flow and dynamic model validation need to be based on WECC-wide disturbances. An example of other model validation need is the outage or disturbance on the major 500 kV or 230 kV

[1]http://www.nerc.com/comm/PC/Model%20Validation%20Working%20Group%20MVWG/Model_Validation_Procedures_2011_12.pdf
[2] The guideline is in its draft version, under review by WECC MVWG
[3] Shared by CAISO through MVWG

transmission system in PC areas that may trigger consequential protection actions or generation tripping.

ColumbiaGrid model validation procedure will primarily focus on either the WECC wide disturbance or the major events of transmission and/or generation disturbances in PC areas. PCs can perform additional MOD-033 work on local and small disturbance based on their availability of real-time data for validation purpose. This would also meet the compliance requirement of R1.1.1-R1.1.4

In order to perform this task, ColumbiaGrid and the members will review and select the events. An event will be selected only if it impacts at least one member's service area, and agreed by both ColumbiaGrid and the participated members for their MOD-033 model validation purpose. Among all notable events, ColumbiaGrid will give priority to events having largest number of members' participation, and larger impact to the system.

The selection of event will be performed with the following steps:

1. ColumbiaGrid will check periodically the WECC System Model Validation Task Force (SMVTF) website for available and suitable West wide System Model (WSM) cases to determine whether those cases are suitable for validation purposes within our members' Area. Suitable WSM cases would have relevant system impacts and monitoring of transmission and generation facilities within the members footprint. If the SMVTF has suitable power flow cases and dynamic data, CG will discuss with the members in the planning meeting. If selected, ColumbiaGrid will use these study cases for its validation purposes.

2. Also, a PC member may recommend ColumbiaGrid to perform validation on a recent event in their system for meeting NERC MOD-033 compliance. This request can be made either in the planning meeting every two months or by submitting a formal request form to ColumbiaGrid. Upon receiving the request, ColumbiaGrid will discuss the event in the closest planning meeting with all members and call for participation.

3. If members agree to move forward using the proposed event, a work group will be formed after the planning meeting. Each member utilities participating the work group will work together and utilize the report for their compliance purpose.

4. The work group will further review the event and related real-time data, base case information. ColumbiaGrid and members will coordinate with Peak RC, individual transmission operators and owners to facilitate the data collection and base case development process. Some disturbance events may not be suitable for MOD-033 validation purposes. These events may include, for example, *asymmetric* events that include highly unbalanced flows such as single pole reclosing or an event that occurred at the top of the hour when generating units are ramping up or down. In study simulation, during initialization process, we assume that all generating units are static with fixed outputs, but over the course of the simulation progress, which

timeframe typically lasts 60 to 120 seconds, some of the units may ramp up or down and they would need additional modeling efforts to further modify the study case and/or sequence of events.

3.2 Event and Data Acquisition

After a notable event is selected and the workgroup is formed, participants will collect data from state estimator (SE), Supervisory and Control Data Acquisition (SCADA), and/or Phasor Measurement Unit (PMU)) for the system and the time. Utilities will requested these data first through the Peak RC. The Peak RC can provide a snapshot from their SE data prior to and immediately after the event. In case the Peak RC does not have available data as requested, the participants of ColumbiaGrid workgroup will collect the real-time data from their own recording facilities.

The Peak RC archives SE cases every 5 minutes and receives over 130,000 real-time measurements that are mapped to the West-wide System Model (WSM). The measurements include analog data (MW, MVARs, kV) and status of the equipment. These measurements are received every 10 seconds via Inter-Control Center Communications Protocol (ICCP) links. If available, SCADA data from each utilities can provide a better granularity for 2 to 5 seconds sampling interval. The workgroup will verify if there were additional switching actions within the time of the saved SE case and the time of the event (theoretically this time frame can be a maximum up to 5 minutes time interval).

Event sequence should be requested from the transmission operators in the area that the event occurred. The workgroup will coordinate with the utilities and transmission operators for the most accurate information for the event sequence. The PMU data will be requested from the transmission operators since the Peak RC does not have all PMU signals available. For the dynamic system model validation, SCADA data alone does not provide sufficient granularity for the transient simulation. Therefore, data from the dynamic monitoring devices, such as PMUs, are needed. If the PMU data from other utilities are needed, the workgroup will coordinate with other transmission operators to request real-time data recordings.

3.3 Peak RC Event and Data Review

After the SE, SCADA, PMU and event sequence data are acquired from either the Peak RC and/or transmission operators or other utilities, the next step is to validate obtained data. For the WSM data, the Peak RC staff will simulate the event using the WSM directly and compare the simulation results to available PMU data. It helps to validate WSM data by Peak RC and to make sure that the WSM snapshot provided for model validation process represents the event accurately since this snapshot will be used as modeling inputs to the WECC power flow base case for pre-contingency operational conditions.

The process of WSM validation is a relatively quick process by the Peak RC since the WSM case is a representation of the pre-event conditions provided by real-time SCADA measurements. Sequence of event information needs to be investigated with the support from the transmission operators, and included in the study. Since the WSM case uses the same dynamic model as the WECC power flow case, all modeling issues found in this process will be reported to the WECC staff who will put together a WECC-wide power flow case and corresponding dynamic data.

3.4 Base Case Development

This section explains a proposed process for base case development

3.4.1 Power Flow Case Development

WECC will prepare power flow case based on the pre-contingency operating conditions using the Peak RC-prepared WSM after the WSM validation is performed by the Peak RC. This process will be performed by the WECC staff. For the peaking condition power flow case or other event based case that cannot be prepared by Peak RC from WSM, ColumbiaGrid staff will prepare the case with the assistance from the workgroup participants.

As indicated in reference [2], this process is the most time consuming part of the process. For this process, the WECC-wide full-loop steady-state model or an existing ColumbiaGrid planning base cases must be modified with generation dispatch, topology and load changes based on the real-time data noted above in order to achieve a close match to an actual system condition for the selected time for the study. Reference [1] from the NERC MWG document provides more details on this process. There could be some limitations on the part where the WECC staff or ColumbiaGrid workgroup can modify the power flow study case for the overall WECC-wide footprint. Additional refinement of the power flow study case may be required by the ColumbiaGrid workgroup participants for their own planning area.

The main intent for validating a steady-state power flow model is to compare the pre-disturbance measurement (e.g. bus voltages, real and reactive power flow on system elements and paths, generation dispatch, phase shifter settings, LTC tap positions, etc.) to the power flow solution from the WECC-wide study case that is being adjusted to the pre-disturbance operating conditions. The desired outcome would be that the results obtained from both power flow simulation and the real-time measured data would match closely. If they do not match closely, it is necessary to investigate the cause(s) of the discrepancies. In the application guide of NERC MOD-033, it states that reasonable changes to the data in coordination with the data provider can be made in the PC area so that it provides a better match to the actual system responses. It is therefore recommended to adjust voltages by allowing LTC taps, SVCs and generators to adjust automatically based on measured conditions and then to compare simulated tap positions and MVAR values to the actual values. This process is helpful to pinpoint the issues and to correct transformer tap positions, regulated buses and transformer impedances. Note that there are differences between the WECC power flow case and WSM (state-estimator snapshot) study case. The difference is mainly due to mismatches that are introduced to the state estimator power flow case during the process of state estimations. The mismatches appear as small MW and MVAr loads as these are added to the WSM study case.

3.4.2 Dynamic Model Development and Data Validation

WECC staff in collaboration with the Peak RC staff will prepare a corresponding dynamic data file for the WECC power flow case posted on the Peak RC website (i.e., WSM website)

for the WECC members' use. For the events selected by the ColumbiaGrid workgroup that does not have a base case prepared by Peak RC and WECC staff, ColumbiaGrid workgroup will follow the similar process to prepare a dynamic data file for use in conjunction with the power flow study cases developed by the workgroup.
After a steady-state power flow model has been developed as described in Section 4.4.1, the workgroup will select the dynamic data file that is available with the approved WECC power flow base case. It may be necessary to have additional steady-state model adjustments as well as dynamic model adjustments, such as generator capability parameter adjustment and new composite load models creating. It is also possible that dynamic models of some units may be netted to provide reasonable system behavior.

It is important that the adjusted dynamic data file is initialized properly with the steady-state power flow model. In other words, generators must initialize within governor limits, missing dynamic models must be created appropriately, and initialization warning/error messages must be addressed. If new additional dynamic models need to be added because they were missing in the original dynamic data, then this change must also be made to the master dynamic data set used in all studies going forward. After the power flow case and dynamic data are prepared, a few transient runs should be performed using the new dynamic data. A no-disturbance simulation should produce flat lines, a ring-down simulation (e.g., insertion of the Chief Joseph Braking Resistor) should produce traces that initially oscillate but damp out acceptably. In addition, a few additional disturbances should be simulated (such as Palo Verde generation loss) with acceptable transient results. All netted generating units in the dynamic model in a specific PC's footprint should be addressed and corrected by the PC with appropriate dynamic models. If new additional dynamic models need to be added to address netted generating units in the original dynamic data, then this change must also be made to the master dynamic data set used in all studies going forward after confirmation with the generator owners.

3.4.3 Creation of Event Sequence for Simulation in the Transient Study

WECC and Peak RC staff will create an accurate sequence of events and switching file after creating the dynamic data, with the assistance from the individual transmission operator where the disturbance occurred. If the ColumbiaGrid workgroup decides not to use the power flow and dynamic data file created from a disturbance event from the Peak RC's WSM website, the workgroup, with the assistance from its transmission operators, will prepare its own sequence of event as well as power flow and dynamic data associated with its selection of the event. This process may take longer to prepare for the full WECC-wide power flow and dynamic data, as the workgroup would need to contact other balancing authority PCs and transmission operators for relevant modeling data to complete the full-loop study case for the specific event or scenario.

The transmission operators whose system the event happened in, would have the most accurate time sequence data. The switching sequence is created based upon the PMU recorded data and other event information such as SCADA dispatcher's log. The Transmission Owners' recording data can also be of great source of information for helping the transmission operators to put together the detailed sequence of events and switching file to be used by the Peak RC and other PCs. Comparison of Dynamic Model to Real-time Data.

3.4.4 Review of Steady-State and Dynamic Model before Final Posting on the Peak RC's WSM Website

The following process applies to the scenario when the ColumbiaGrid workgroup selects the disturbance event and corresponding WECC-prepared power flow case and dynamic data as well as the sequence of events that are posted on the Peak RC's WSM website for compliance with the MOD-033 Standard. The review process will be similar if the workgroup decides to create its own power flow case and dynamic data for its own PC Areas that is not available from the Peak RC WSM website.

After the WECC study case (steady-state model and dynamic model) has been created by the WECC staff, the case will be available to Planning Coordinators (PCs) within WECC and are posted on the "peakrc.org" WSM website. The parameters that should be reviewed include bus voltages and reactive sources to ensure an acceptable voltage profile, generation dispatch or output levels, power flow on transmission system elements including WECC paths, loads, etc. By the end of the four-week review, all comments and/or corrections are submitted to the WECC staff for incorporating into the final steady-state power flow and dynamic model for posting on the Peak RC's WSM website.

As ColumbiaGrid is neither a PC nor a member of Peak RC, the model review for the Peak RC's WSM cases may not be performed directly by ColumbiaGrid staff. However, ColumbiaGrid may help to facilitate workgroup participants for their review process or review the case if it can access the data.

3.5 Validation and Comparison of Steady-State Power flow and Dynamic Model to Real-Time Recorded Data

After the disturbance event and corresponding power flow case and dynamic model are developed, either by WECC and Peak RC, or by ColumbiaGrid workgroup, the workgroup can choose to utilize an event of interest for MOD-033 validation and compliance. To perform validation on the power flow and dynamic model, each participants will identify several major facilities in their own PC area that are impacted by the events. These facilities may include bus, generator, and transmission facilities. Each participant submit a list of comparison objects such as bus voltage, line flow, loads to the workgroup. All lists form a complete table of objects that should be used for model validation comparison. Post-event values are compared first for steady state power flow validation. Further adjustment may be required with additional model mismatch being captured post the event. Steady State base case can then be adjusted as described in section 4.4.1. After the steady state power flow validation, simulation of the events for dynamics will be compared for the submitted objects.

ColumbiaGrid develops guidelines for R1.1.3 and R1.1.4 requirements. These guidelines are discussed further in the following Section 5 and 6. The R1.1.3 requirements are guidelines which ColumbiaGrid will use to determine unacceptable differences in performance under R1.1.1 (comparison of performance of the ISO's portion of the existing system in a planning power flow model to actual system data) and R1.1.2 (comparison of the planning dynamic model to actual system response). In R1.1.3, the comparison process should take into account the accuracy of available measurements (accuracy class of potential transformers (PTs) and current transformers (CTs)). This effort can be coordinated with the transmission operators and owners where the recorders are installed. Some PMUs also have large offset compared to SCADA measurements. The workgroup will utilize the recorded data from SE and PMUs to the extent that they are available from the Peak RC and/or operators for the power flow and dynamic model validation process, using the data and study cases posted on the Peak RC WSM website.

3.6 Post Event Model Discrepancies and Base Case Adjustment

After the power flow and dynamic base cases are developed for the pre-event condition as described in Section 4.4.1 and 4.4.2, the base case may need further adjustment due to the post-event mismatch, caused by model discrepancies or errors. For example, SVC post event switching may fail to operate in the simulation due to an erroneous switching threshold being modeled. Such a model problem may be caused by an upgraded device using an old model. Only post event comparison can capture these type of model errors after they are triggered. On the other hand, power system dynamics is contributed by all involved devices, model errors or discrepancies from multiple devices may be entangled with, and sometimes exaggerated by each other. To locate each problems, iterative process of comparison may need to isolate and correct some identified issues. This iterative process will need constant adjustment to the base cases.

ColumbiaGrid workgroup will review the post event comparison result and identify the potential causes for the model discrepancy. Each participant may verify with their transmission owner or generation owner for potential modeling problems. Comparison and base case adjustment will be performed iteratively to achieve better comparison result and capture major discrepancies.

3.7 Validation Result Reporting

In each workgroup meeting, the latest validation progress will be reported to the workgroup participant for review and discussion. ColumbiaGrid will coordinate participants for their updates based on the action items after the meeting. After validation work is completed, ColumbiaGrid will develop the reports together with the workgroup participants and keep the report as evidence.

4. Guideline for Determining Unacceptable Difference

This section discusses the proposed guidelines for determine unacceptable differences from the comparison of power flow and dynamic simulation results

4.1 Comparison of Power Flow Model to Actual Data

The first task for validation process is to compare the power flow model solution with real-time data for the selected event. Using computer power flow models, each power flow solution computes mathematically bus voltages and angles in the network, and bus angle is directly coupled with line flows. Therefore, the validation comparison will be primarily focused on bus voltages and line flows between computer models and recorded actual data.

In this process, exact matches for power flows and bus voltages are not expected. However, it is desired to replicate the actual recorded values to the greatest extent possible in the power flow case. As a starting point, ColumbiaGrid will utilize the suggested bandwidth from the NERC's "Procedures for Validation of Power flow and Dynamic Cases" as a guide as discussed in the following. In the future, these bandwidths can be improved and refined with additional model validation experience.

- Modeled power flows should be targeted to be within ±10% of measured data.
- Modeled voltages should be within ±5 % of measured data.

Limitations of system SCADA measurements and potential error in measurement must be recognized and noted in the validation process.

The following is a table summarizing parameters for comparison of power flow performance to actual data.

Parameters for Comparison	**Proposed Bandwidth for Comparison**
Power flows • Lines and transformers • Generators • Interface/paths • Reactive supports	+/-10% (AC) +/-5% (DC) or 100MW Whichever is larger
Voltages • Transmission buses, generator terminal, DC lines' terminals, reactive supports	+/-5%

The following quantities are suggested to be compared if data are available

- Real power output of system slack and area slack machines
- Generator reactive output and voltage
- Line and transformer real and reactive flows
- Interface flows – real and reactive
- Under-Load Tap Changing (ULTC) transformer tap position and voltage
- Phase-shifting transformer angle position, MW and Mvar flows
- Bus voltages and angles
- Static VAR devices reactive output and voltage
- DC lines' terminal voltage, MW flows, and reactive power consumption

For the Power Flow mismatches identified during the validation process, Workgroup participants will review the mismatch and provide updates on some known inconsistency between model and measurement during the meeting. Engineering judgment and knowledge is then used to identify issues with power flow modeling parameters. After identifying and correcting such modeling errors in the power flow case, the updated power flow case is re-solved again and the comparison process is repeated until the results are within the suggested bandwidths as described above. Detailed examination of these parameters must be performed during each comparison, and several bus-by-bus adjustments to load and power factor may be required to obtain a good correlation to the observed system voltages and flows. When the comparison is deemed satisfactory (within suggested bandwidths), the resulting power flow solution is an acceptable representation of the system conditions at the selected time. After the power flow model is validated, it can be used to initialize a dynamic simulation for validation of the dynamic model.

4.2 Comparison of Dynamic Model to Actual Data

The first step of comparing the response of an interconnection-wide dynamic case to dynamic data recordings is to develop a compatible pre-event power flow case (see Section 4.4.1 for further details). The elements modeled in this power flow case must be aligned with the corresponding dynamic model data for initialization.

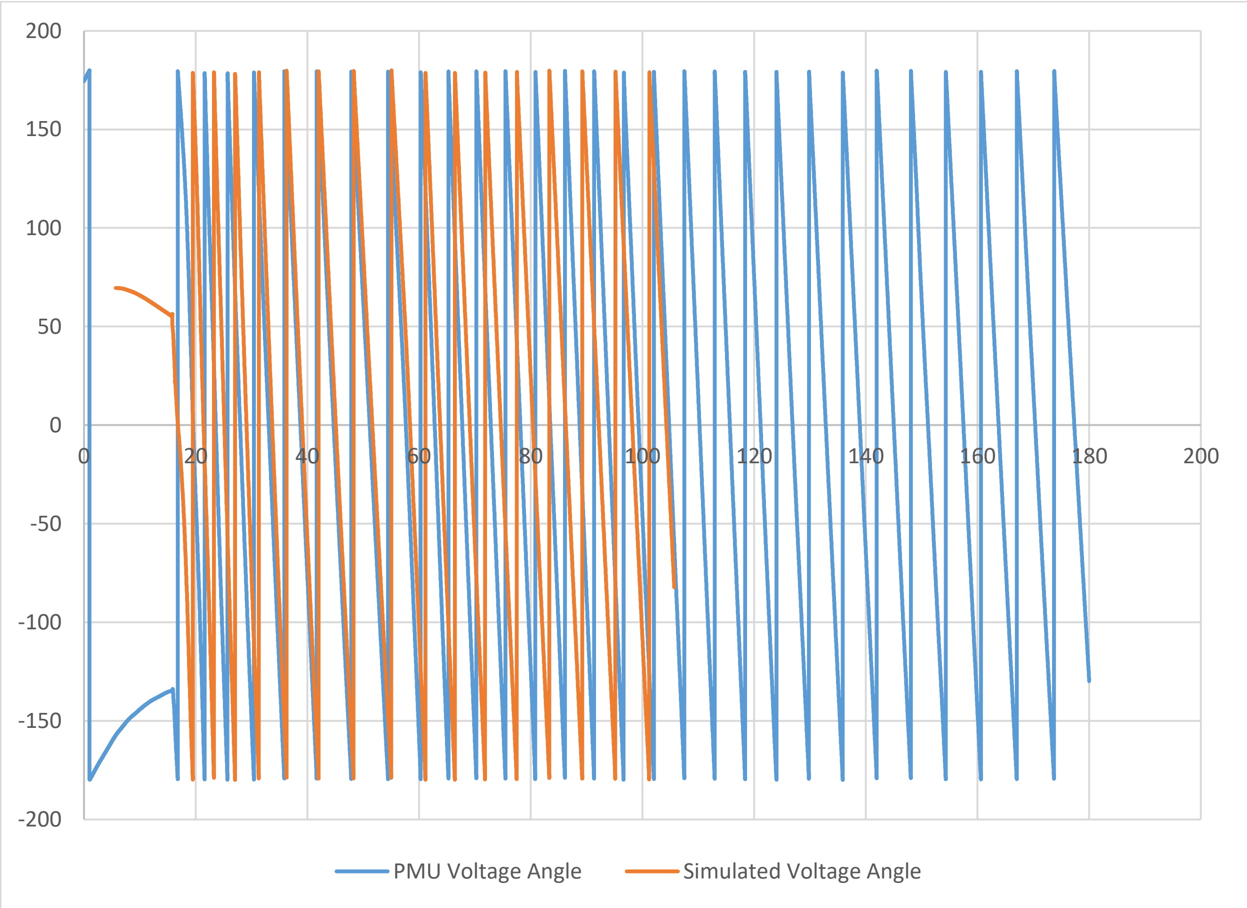
After obtaining a satisfactory power flow base case for pre-event conditions, a specific system disturbance (i.e., an event) is simulated using transient stability program such as PowerWorld with the developed dynamic data (see Section 4.4.2 for further details). The simulated result will be used to compare with the actual recordings from EMS/SCADA and PMU data for the selected event.

The primary adopted methodology for ColumbiaGrid dynamic comparison is to plot simulation results on the same graph as the actual system response, with a visual inspect to see if the trajectories are following the same trend closely.

In addition to visual inspection, metric of bandwidth for various quantities can be used to further evaluate the similarity between measurement and simulation. The following are proposed bandwidths for various quantities for dynamic model validation, if the data are available:

Dynamic Model Validation Parameters for Comparison	Proposed Bandwidth
Bus frequency	+/2%
Bus voltage magnitude and angle	+/-5%
Generator real and reactive output	+/-10%
Line and transformer flows – real and reactive	+/-10%
Static and dynamic VAR devices reactive output and voltage	+/-10%
DC lines' active power, terminal voltage and reactive power consumption	+/-5%

It should be noted that even though comparison results lies within the proposed bandwidth provide an indication of good similarity or acceptable response. It does not necessarily imply that a violation of the bandwidth is a bad one, or unacceptable response. This can be illustrated from the following example:



The plot shows a comparison between bus voltage angles from a simulated case and PMU sample data for a true event. For this event, a good match between simulation and real-time data are obtained. Voltage, Power Flow and frequency are all displayed great similarity in trend and lie within small variation with each other. For bus voltage angle comparison showed above, it also shows good similarity by visual inspection, as the oscillation frequency and magnitude are almost identical. However, if the metric bandwidth is adopted, almost all sample points the difference between PMU data and simulation are close to 100%. Several reasons contributes to this observation:

1. Voltage angle are very sensitivity to generator rotor speed and system frequency. A very small variation of frequency may accumulated to large deviation of angle.

2. Voltage angle does not have an absolute reference values. It is a quantities only use relative values.

3. During an event with oscillation, quantities along the dynamic trajectories normally have a wide range of value themselves. Small mismatch or measurement error (e.g. 0.1 degree) may lead to a big variation of percentage error (e.g. 50% when angle = 0.2 degree, but only 0.1% when angle = 100 degree). This is true also for other quantities such as bus voltages, line flows, real and reactive power output whose quantity values can be varied from 0 to large values.

4. Dynamic simulation is a dynamic process. It is typically impossible to be fully described by just one or several metric quantities. For certain quantity (such as bus voltage angle) under a certain event scenario (such as oscillation), different metric need to be selected and reviewed case by case to provide a better indication of comparison. E.g., angle values is not a good metric to be used in the above case, but angle oscillation frequency and magnitude provides a better indication of similarity.

For these reasons, bandwidth will be evaluated as a part of model validation only for information only. Dynamic quantities normally does not share sensitivities to the large pool of potential mismatches that can be hardly identified or quantified, such as measurement errors, non-modeled dynamics or parameter variation. These metric will be helpful to develop the knowledge base during the process of performing MOD-033 tasks. However, conclusions such as whether or not a certain metric will be a reasonable indication of acceptable validation result need to be evaluated further after establishing the knowledge base of the whole region under various conditions.

5. Guideline for Resolving Unacceptable Difference

If the comparison yields unsatisfactory (i.e., not meeting the specified bandwidths) result, there are potentially two basic causes: (a) the measured data may have significant errors; and (b) there are some power flow or dynamic model parameters mismatches. These mismatches includes but not limited to:

Power Flow Parameters:

- Incorrect transmission network model values
- Line impedance and charging
- Transformer impedance and fixed tap position
- Reactive shunt devices size
- Reactive series devices size
- Incorrect modeling of substation bus split
- Load distribution on each of the buses across the system may differ significantly from the actual system conditions
- The power factors on each load bus in the original case may differ significantly from the actual power factors for the system conditions
- Non-existent transmission elements modeled in the power flow case

Dynamic Parameters:

- Excitation control parameters and status
- Power system stabilizer (PSS) control parameters and status
- Governor control parameters and status
- Generator inertia, impedance and time constants
- Voltage compensation impedance and control point
- Power Electronics devices control
- DC line control
- FACTS devices control and switching
- Load model

The first step of resolving unacceptable difference is to identify the causes of the mismatches. These efforts will be performed ColumbiaGrid staff with participated utilities and reported to the workgroup during the meeting. It should be noted that it is not possible to provide specific guidelines as to which dynamic model parameters could have the primary impact without reviewing the comparison result in details. In many cases, a mismatch at a particular location suggests a need to individually validate the dynamic models of the system components in that vicinity. This is a time consuming process [3].

After identifying a group of model candidates for dynamic mismatches, these mismatches will be evaluated based on various factors that may contribute to the mismatch. These factors include but not limit to:

- Device Models' mismatch
- Non-modeled Dynamics and switching behaviors
- Uncaptured events including protections and remedial actions
- Measurement Errors

- Calibration needs for Generic model (Wind, Solar, Load, etc.)
- Simulation Software limitation

To resolve the unacceptable difference, ColumbiaGrid workgroup will develop reports and coordinate to the PCs, data owners, Peak RC and WECC. Communication and solution will be kept as evidence for this step by ColumbiaGrid.