Verification of the Generic Model for Inertial-Based Fast Frequency Response of Wind Turbine Generators

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Technical Update, September 2019

EPRI Project Manager

E. Farantatos

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Power and Energy, Analysis, Consulting and Education, PLLC (PEACE®)
2221 Justin Rd #119-414
Flower Mound TX 75028

Principal Investigator
P. Pourbeik

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ABSTRACT

The Electric Power Research Institute (EPRI) continues to be actively engaged in the development of generic and public models for renewable energy systems through a broad industry-wide effort. The work is performed primarily within the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force (REMTF), whose members include many of the major equipment vendors and the major commercial software vendors in North America.

This document presents the results of work related to the development of a simple generic model for emulating the so-called "synthetic" inertia supplemental controls that are now offered by many of the major wind turbine manufacturers. The terminology used here refers to this function as inertial-based fast frequency response. A brief background is presented on the concept. The proposed model specification was presented in the 2018 EPRI technical update *Generic Model for Inertial Based Fast Frequency Response of Wind Turbine Generators - Technical Specifications* (EPRI report 3002013641). In this technical update, for 2019, that proposed model is tested and verified against the actual field measured response of a large wind power plant.

Keywords
Emulated inertia
Inertial-based fast frequency response
Modeling
Synthetic inertia
Wind turbine

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1 INTRODUCTION

Controlling the nominal system frequency in large interconnected power systems continues to be a significant part of system reliability [1]. The most common criteria used to assess adequate system frequency response, is the ability of the power system to respond in a stable fashion to forced outage of the largest generating facility on the system, under the most onerous conditions, and for the system frequency to settle down at a new equilibrium such as to avoid any under-frequency load-shedding. Since most large power systems today are still dominated by synchronous generation, for such an event, the frequency response of a typical power system will be as depicted in Figure 1-1. There are three distinct periods in the frequency response of the system (i) the initial *inertial-response* of synchronous generators, (ii) the *primary frequency* response of generators and load damping, and (iii) *automatic generation control* (AGC) which brings frequency back to its nominal value over several minutes.

The period of inertial response of the system is an inherent physical response of synchronous generation to a sudden imbalance in generation and load. Inverter-based generation (IBG) technologies, such as type 3 and type 4[1] wind turbine generators (WTG), solar photovoltaic (PV) generation and battery-energy storage systems (BESS), do not inherently provide such a response. Such IBG need to have controls implemented in order to provide any type of frequency response. All of them are certainly capable of providing frequency response and can do so quickly and decisively (e.g. [2] and [3]).

In the case of PV and BESS, there are no mechanically moving parts (e.g. rotating turbine) and the energy conversion is from dc current either produced by the photovoltaic effect in a solar-cell or a chemical process in a battery. Thus, the frequency response from a PV or BESS is a sustained response and requires keeping some head-room/reserve in the amount of available incident energy. That is, PV and BESS can provide very fast and decisive primary frequency response. In the case of a BESS this simply means having adequate charge in the battery. For a PV system it means operating the PV at a sub-optimal point (i.e. not at peak efficiency as determined by the maximum power tracking point, see [2]). In the case of the BESS this constitutes a capital cost for installing the BESS and cost of energy storage. For the case of PV, it can constitute a significant opportunity cost (i.e. cost of not producing and selling the maximum amount of incident solar power that can be converted to electricity at any given time). For wind generation, a similar approach is also possible and has been demonstrated many times, by many vendors, in the field. Namely, to "spill" some of the incident wind energy and keep it in reserve to provide primary frequency response when called upon to do so. Again, this constitutes a significant opportunity cost. That is, lost revenue from the "spilled" energy that could otherwise

[1] Older type WTGs, namely type 1 and 2 WTGs, do have some inherent inertial-response similar to synchronous generators since they are directly coupled induction generators (See https://www.nrel.gov/docs/fy12osti/55335.pdf). However, these technologies are slowly being replaced in the field by type 3 and 4 WTGs and most, if not all, major WTG manufacturers no longer supply these older technologies, certainly not for large wind power plants connecting to the bulk electric system. Therefore, the discussion in this report focuses on inverter-based WTG technologies, namely type 3 and 4 WTGs.

have been converted to electricity and sold at the time it was available. Such economic considerations are outside of the scope of this document.

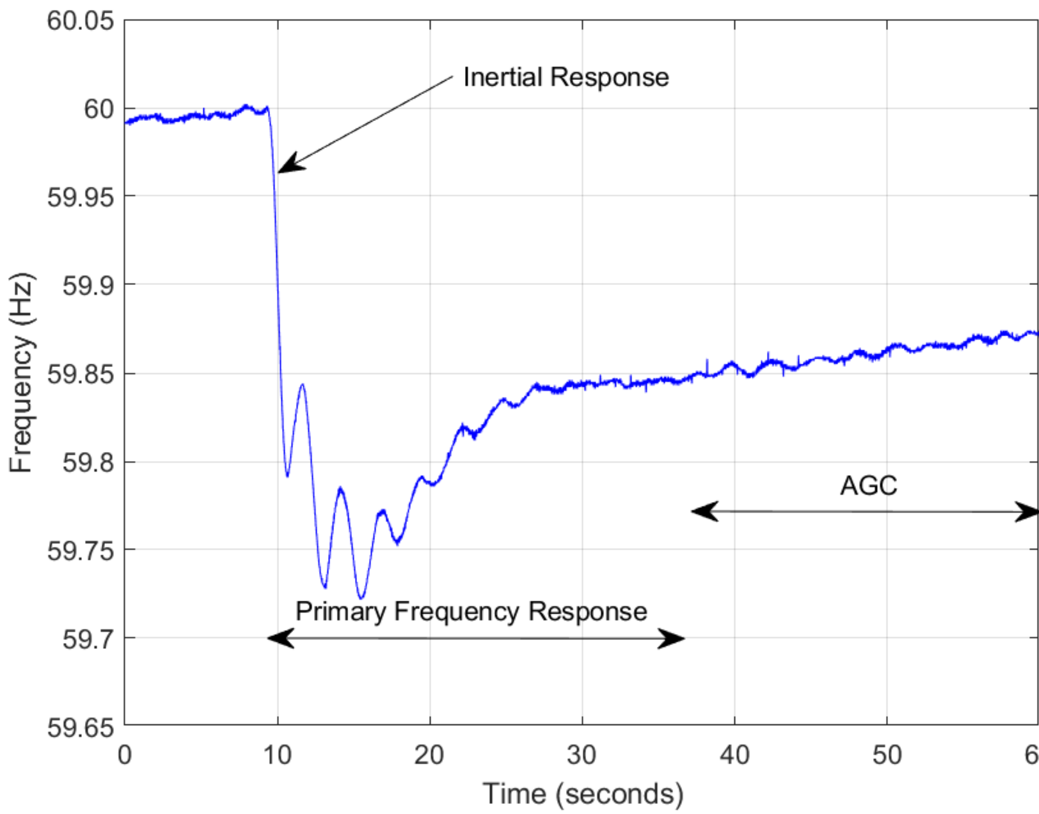

Figure 1-1
Actual recording of an under-frequency event on a large power system

In the case of WTGs, the rotating mass of the wind turbine and electrical generator constitutes a very large amount of stored rotational mechanical energy, similar to large synchronous generators. In general, the stored rotational energy in the rotating mass of the turbine-generator on a typical WTG is anywhere between 4 to 6 MWs/MVA. Thus, with the proper additional supplemental controls, it is possible to extract some of this rotational energy and to momentarily inject it into the grid, through proper control of the inverter interface. This additional possible functionality with WTGs is sometimes referred to in the literature as "emulated" inertia for WTGs, or "synthetic" inertia. Here we prefer to refer to this functionality as *inertial-based fast-frequency response* (IBFFR) of WTGs. It is important to understand that this functionality is different to sustained primary frequency response, which is what was briefly discussed in the preceding paragraph.

Many of the major WTG manufacturers do offer an IBFFR functionality for their type 3 and/or 4 WTGs. This is a supplemental control that is an add-on to a WTG and not a standard feature. Also, the particular WTG vendor should be consulted to identify if the feature can be retrofitted to older WTG models.

In the 2018 technical update, a new simple and generic model structure was proposed for emulating the performance of IBFFR for WTGs [4]. In this document the model structure will be briefly presented again in section 2, for the sake of completeness. However, the key new contribution of this document is the verification of the efficacy of this simple model, by illustrating its performance as compared to actual measured response of a large wind power plant which was field tested to illustrate its IBFFR response. This comparison is presented in section 3.

2
REVIEW OF IBFFR MODEL STRUCTURE

2.1 An Overview of the IBFFR Functionality

The details of the implementation of IBFFR for various WTG manufacturers, is clearly proprietary and vendor specific. However, there are some high-level characteristics of the dynamics of achieving IBFFR for WTGs that are seen in all implementations for the various vendors [5], [6], and [7]:

1. The IBFFR is achieved on an individual WTG basis and then the aggregated response is seen at the point-of-interconnection of the WPP. That is, each individual WTG attempts to extract some rotational stored energy out of the WTG rotating inertia and to inject it into the grid.
2. The amount of power that is extracted out of the rotating turbine is typically limited to about 5 to 10% of WTG rating. Also, the actual amount of power injected by this function at any point in time is typically a percentage of the instantaneous power output of the WTG at the time IBFFR is initiated.
3. By extracting energy out of the rotating wind turbine, the turbine speed is reduced, lift reduces, and the turbine is now operating at a sub-optimal point. The energy needs to eventually be put back into the turbine to bring it back to optimal speed and account for losses due to reduced lift. This is not true if the incident wind speed is above rated wind speed since the additional energy can then be extracted out of the surplus incident wind energy.
4. IBFFR cannot be provided if the initial wind speed (and thus turbine speed) is too low – typically IBFFR is not provided if the WTG is below about 20% or so of rated power.
5. In the actual implementation of IBFFR, various mechanical and electrical equipment limitations must be respected.
6. The above facts thus mean that:
   a. The amount of IBFFR available at any given time for an entire wind power plant is somewhat stochastic, since it depends on:
      i. the number of WTGs on-line, and
      ii. the wind speed and turbine-speed of each individual WTG that is on-line.

It is imperative to understand the final point above (item 6). This is because unlike other functionality of IBG (such as volt/Var control or primary frequency response), even when deliberately initiated in the field by a test signal, the exact IBFFR achieved at any one time will be a function of the wind speed and turbine speed at each and every WTG in a WPP at the moment the test is initiated, as well as how the wind speed varies at each turbine for the duration of the test.

2.2 The Simple Generic IBFFR Model Structure

The proposed model structure for IBFFR was described in [4], and publicly presented to the WECC Modeling and Validation Working Group in its November 2018 meeting [8]. The general shape of IBFFR can be depicted as shown in Figure 2-1.

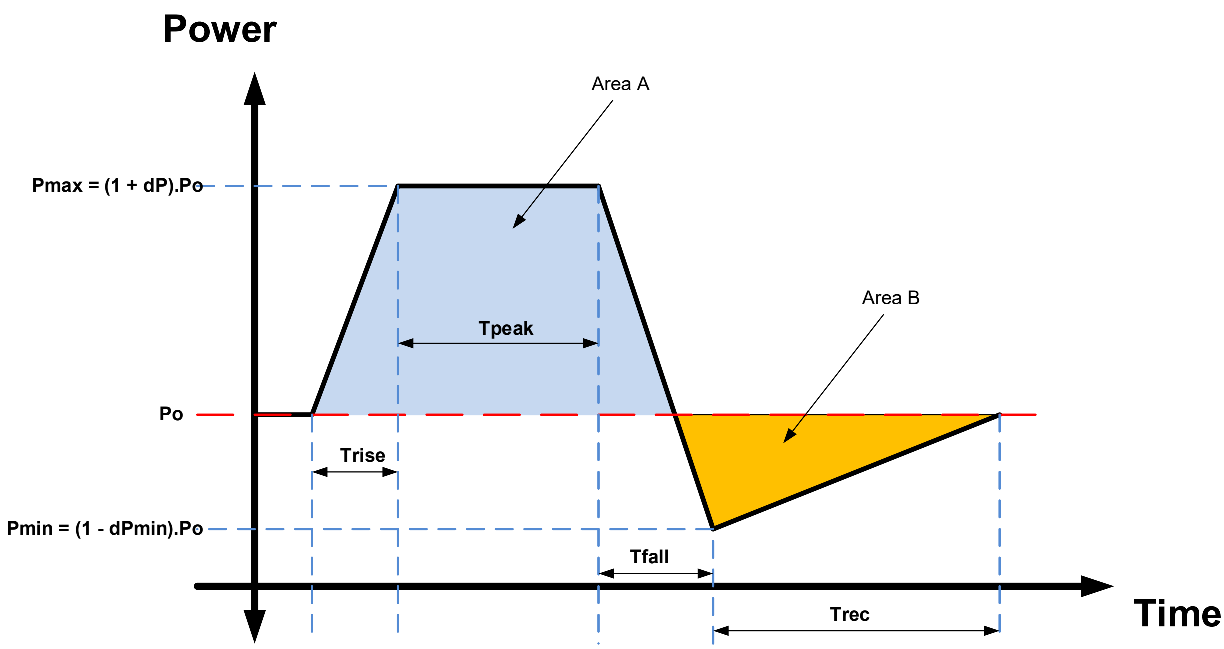

Figure 2-1
Characteristic of the IBFFR

The process of IBFFR follows basically the following path:

1. An under-frequency event occurs on the system.
2. Once frequency goes below a certainly value (outside a defined deadband), then IBFFR starts.
3. The power of the WTG is increased to a higher level (*Pmax*), which depends on the incident wind speed and WTG turbine speed. It takes a given amount of time (*Trise*) for the power to increase to this value.
4. The power is sustained at the new level for a given amount of time (*Tpeak*).
5. Then the WTG power starts to drop at a steady rate, until it hits a minimum level (Pmin). There is a limit to how low *Pmin* can be.
6. Finally, the WTG power recovers (*Trec*) to its original output, prior to the event, assuming wind speed has not changed.

The energy delivered is given by Area A. The energy taken back from the system is given by Area B. In a real system Area B is likely slightly greater than Area A, since not only does the turbine need to be returned to its original speed, but also there are losses in the process that will need to be covered (e.g. such as loss of lift). However, in stability level generic models such losses are not modeled and therefore for the purposes of the simple model developed in [4] and presented again here, it is assumed that Area A = Area B. An important note is that if the incident wind speed is above rated wind speed (i.e. significantly greater than the wind speed at which the WTG produces it rated MW output) then Area B will be essentially zero, since the additional energy can be extracted out of the surplus wind energy. Since the generic models do not have wind speed as an input, if the user is simulating such a scenario, they need to so parameterize the model to effectively make Area B close to zero, e.g. set *dPmin* = 0.001 pu.

A simple user-written model was developed in GE PSLF^{TM} to demonstrate the proposed model for IBFFR. It is based on Figure 2-1. The model, the underlying assumptions behind it, and its functionality may be explained in more detail in [4] and [8]. Here we do not repeat all those details but do still provide a brief summary of the key features.

Although, the details of the IBFFR are likely quite different among the various wind turbine generator manufacturers, for the purposes of a generic model one can define four (4) regions in the response, as shown in Figure 2-1, namely:

- *Trise* – which is the time it takes for the power of the unit to rise from its initial power to the peak value during the IBFFR.
- Tpeak – which is the time (duration) that the WTG remains at the peak value of the IBFFR, with the peak of response being a percentage of the initial power, i.e. $Peak = Po \times (1 + dP)$
- *Tfall* – which is the time it takes for the power to fall back down, and typically (when the incident wind energy is below rated wind power) the turbine will fall below its initial power output. It will fall to a level that is a percentage of the initial power, i.e. $Pmin = Po \times (1 - dPmin)$.
- *Trec* – which is the time it takes for the power to recover back to its initial value; this is the time during which energy is given back to the rotor to bring it back to its initial speed.

These parameters thus define the dynamic behavior of the IBFFR. There is, however, a few other caveats that are discussed in the points that follow. Also, there is one other parameter that is needed, namely the deadband (*dbd*) in frequency. When the frequency, as measured at the WTG or wind power plant level, falls below (1 – *dbd*) [pu] then the IBFFR function is initiated. Also, ***note that this supplemental control is only initiated for under-frequency events and for a decrease in system frequency.***

With the above in mind the proposed model is shown in Figure 2-2, and Figure 2-3 shows how it fits into the mix of the generic 2nd generation renewable energy system (RES) models. The model may be explained as follows:

- The error in frequency is calculated (*err*) where frequency is measured at the point-of-interconnection of the wind power plant[2]. The function F1 represents the following simple logic: *if err ≤ dbd then out1 = 0, else out1 = 1*. Thus, when frequency falls by more than *dbd* [pu] the IBFFR control is initiated.
- The function F2 represents the following simple logic: *if s0 ≥ dP.Po then out = 1, else out = 0*. Then *out2 = out* (the output of F2) after a delay of *Tpeak* seconds.
- The function F3 represents the following simple logic: if s1 ≤ -(dP + dPmin).Po then out3 = 1, else out3 = 0.
- The rise for recover (Trec) can be calculated from the other parameters (and is not a user-input) in order to ensure that the energy taken out of the shaft is equal to the energy returned to the shaft (see [4] or [8] for the equation to calculate Trec).
- Finally, a perusal of the table of parameters (Table 2-1) will show that we have assigned six (6) sets of values of *dP, dPmin, Trise, Tpeak* and *Tfall*, associated with six different power levels of the turbine (*p1* to *p6*). The actual amount of IBFFR available from a WTG is dependent of the incident wind energy (wind speed) and the rotation speed of the shaft. However, for the generic RES models wind speed is not an available input and the shaft speed is not available for some of the type 4 WTGs. Thus, we have made the assumption that the initial power output of the WTG (in per unit of the rated output) is a reasonable indicator of both these variables (i.e. incident wind speed and rotor speed). The pseudo code of this is provided in [4] and [8].

[2] Measuring frequency at the POI bus is perhaps preferred in the software programs to minimize the issues related to frequency calculation in positive-sequence programs to the extent possible (see https://www.wecc.biz/Reliability/WECC_White_Paper_Frequency_062618_Clean_Final.pdf)

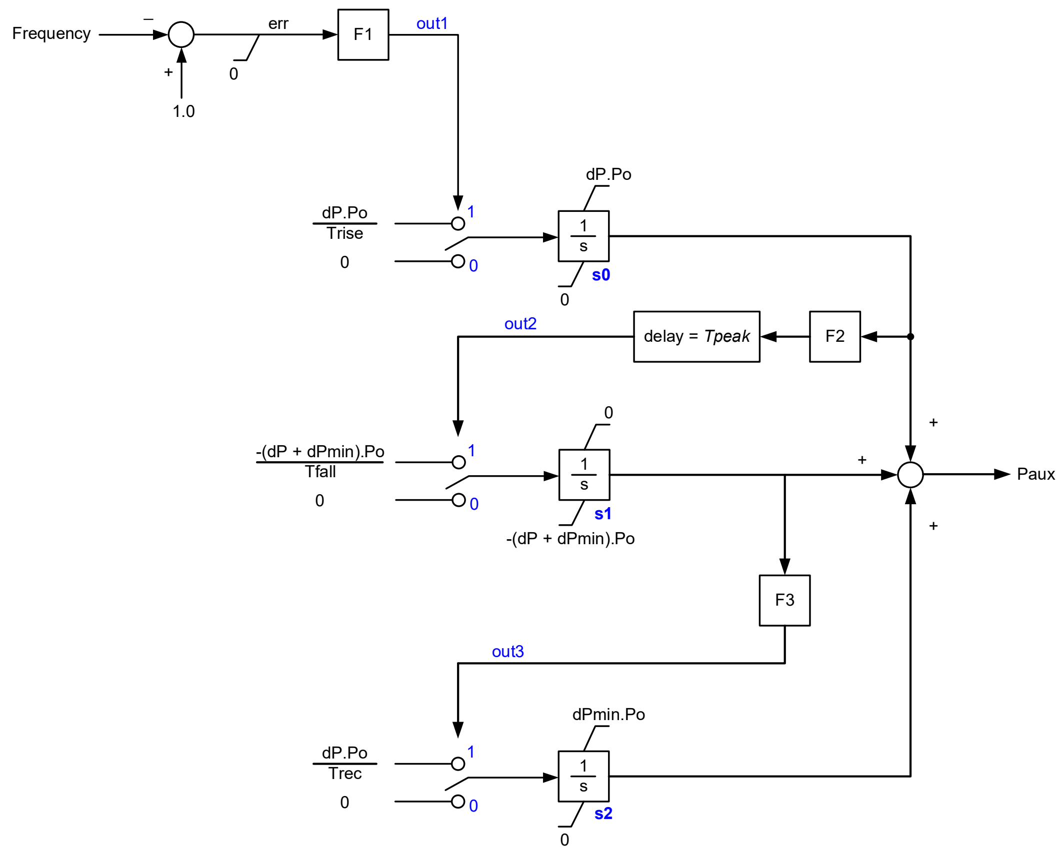

Figure 2-2
Block-diagram of the implemented WTGIBFFR_A model

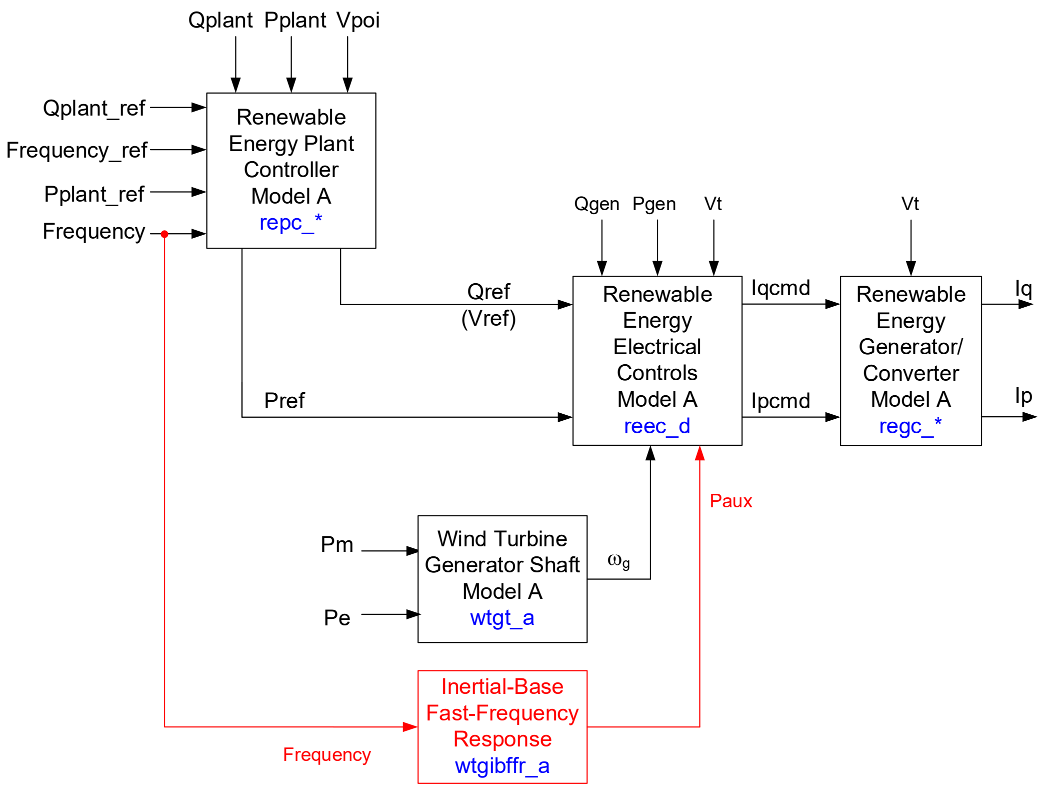

Figure 2-3
High-level block-diagram showing, as an example for a type 4 WTG, how WTGIBFFR_A fits into the RES models. For a type 3 WTG, it would work the same

Table 2-1
Parameter List for WTGIBFFR_A model[3]

Parameter	Description	Typical Range/Value[4]
dbd	Deadband below which IBFFR is initiated, that is when (1 – frequency) ≥ dbd, then the IBFFR is initiated [pu]	0.0008 – 0.0017
[p1, p2, p3, p4, p5, p6]	Six (6) power points corresponding to the six sets of parameters [pu]	N/A
[dP1 to dP6]	Six dP values (see Figure 2-1) [pu]	0.05 – 0.1
[dPmin1 to dPmin6]	Six dPmin (or Trec) values (see Figure 2-1) [pu] (or [s])	0.01 – 0.08
[Trise1 to Trise6]	Six Trise values (see Figure 2-1) [s]	0.1 – 0.2
[Tpeak1 to Tpeak6]	Six Tpeak values (see Figure 2-1) [s]	1 – 2
[Tfall1 to Tfall6]	Six Tfall values (see Figure 2-1) [s]	0.2 – 2

[3] As of August 19, 2019, after the August meeting of the WECC MVWG, there was a suggestion by one vendor to add another array of parameters to the IBFFR model, namely a set of user-specified *Trec* values. This was agreed to by the group and has since been added to the model. However, it has no impact for any of the simulation work shown here. This was tested and confirmed. The reason is as follows. The six (6) *Trec* values in the model should typically be set to zero (0). By doing so the model internally calculates the value of *Trec* for each operating point using equation (1) in reference [4]. If, however, the user wishes to define a *Trec* that is greater than the calculated value using equation (1) as specified in [4] for each of the designated six operation points, then the user may populate the *Trec* parameters. This may be done in cases where the user may wish to represent the fact that Area B (in Figure 2) is actually larger than Area A in some cases due to losses during the period of power injection as the turbine speed significantly declines from its optimal point of efficiency. In doing so, it must be noted that since positive sequence models do not represent such losses, by making Area B larger, the speed of the machine in simulation may end up artificially higher at the end of the simulation. Furthermore, if the user defined a value for *Trec* that is less than the value calculated internally by the model (equation (1) in reference [4]), then the model will ignore the user defined value and use that calculated value. This is because, except under operation when the incident wind speed is greater than rated wind speed, in all other cases Area B must always be either equal to or greater than Area A.

[4] The typical range of values provided here are not necessarily representative of what can actually be accomplished by specific equipment in the field. This will require further study and coordination with vendors to come up with more reasonable and suitable numbers.

3

MODEL VERIFICATION AGAINST FIELD MEASURED RESPONSE OF AN ACTUAL WIND POWER PLANT

The purpose of this section is to provide some evidence as to the efficacy of the proposed simple generic model for modeling the inertial-based fast frequency response (IBFFR) of wind turbine generators (WTGs). For this exercise, a wind turbine manufacturer, through a non-disclosure agreement, graciously provided to PEACE® the measured response, at the point-of-interconnection (POI), of a large transmission connected wind power plant (WPP), as recorded during staged field tests performed to demonstrate the emulated inertial-response control feature of their wind turbines. The vendor asked to remain anonymous, and furthermore to not disclose any details about the plant in question, or any of the raw data. However, they very kindly agreed to the release these results to inform the industry. EPRI graciously funded this simulation work and the preparation of this report. These results will also be shared at the WECC Modeling and Validation Working Group meeting in August 2019, and so will be publicly shared, as agreed ad requested by the wind turbine manufacturer.

Three events were recorded, for three different operating conditions, for the same WPP. In each case the same test signal was applied to the WPP, which was the injection of a "synthetic" frequency signal into the plant level controls to emulate a sudden drop in system frequency, followed by being then restored. A simple model of a WPP connected at the POI to an infinite bus was developed in GE PSLF™ (see Figure 3-1), and then the playback feature was used in GE PSLF™ to play the exact same frequency signal played into the plant controller in the field into the model at the POI of the WPP model. The parameters for the model are shown in Table 3-1. An important note is that the parameters used here were tuned to give a reasonable emulation of the observed behavior of the WPP. They are NOT to be taken as the final and actual settings in the WPP, nor to be exactly representative of any vendor's equipment. The results are shown in Figure 3-2.

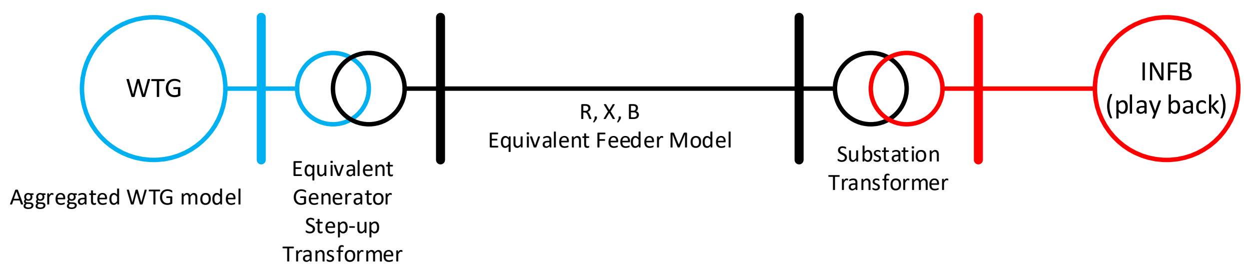

Figure 3-1
Simple WPP model

Table 3-1
Parameters used for the WTGIBFFR_A model verification

Parameter	Description	Typical Range/Value
dbd	Deadband below which IBFFR is initiated, that is when (1 – frequency) ≥ dbd, then the IBFFR is initiated [pu]	0.0017
[p1, p2, p3, p4, p5, p6]	Six (6) power points corresponding to the six sets of parameters [pu]	{0.3, 0.5, 0.6, 0.7, 0.8, 0.9}
[dP1 to dP6]	Six dP values (see Figure 1-1) [pu]	{0.06, 0.06, 0.06, 0.06, 0.06, 0.06}
[dPmin1 to dPmin6]	Six dPmin values (see Figure 1-1) [pu]	{0.05, 0.05, 0.04, 0.02, 0.02, 0.02}
[Trise1 to Trise6]	Six Trise values (see Figure 1-1) [s]	{1.5, 1.5, 1.5, 1.5, 1.5, 1.5}
[Tpeak1 to Tpeak6]	Six Tpeak values (see Figure 1-1) [s]	{9, 9, 9, 9, 9, 9}
[Tfall1 to Tfall6]	Six Tfall values (see Figure 1-1) [s]	{1.5, 1.5, 1.5, 1.5, 1.5, 1.5}

A perusal of the simulation and measurement results in Figure 3-2 lead to the following observations:

- The results are actually quite reasonable. Certainly, the match between simulation and measurement is not perfect but it is quite reasonable given the extreme simplicity of the model.
- It should be noted, that the assumptions for parametrization of the simple model (Table 3-1) for power levels below 0.5 pu are not necessarily valid since there were no field measured results to compare with below 0.5 pu plant output. Also, at a certain power level, here we are assuming 0.3 pu power (parameter *p1* in Table 3-1), the IBFFR function is longer available. Here the value in the simple model is an assumption and is NOT the limit for this or any vendor. Nevertheless, there is always some lower limit of power below which IBFFR is no longer available. Also, this limit applies on a turbine by turbine basis, which is hard to capture faithfully with an aggregated model since in real life within a power plant, at any given time, due to the spatial variations in wind speed across the power plant, some turbines may be below this limit, while others may be above.

Based on these results it may be concluded that the simple generic IBFFR model is reasonable for use in planning studies, with an understanding of the following, that the actual IBFFR that is supplied by each individual turbine in a wind power plant is dependent on many factors, such as (i) the incident wind energy (wind speed) on a turbine, and (ii) the initial speed of the rotor of the turbine. When performing large scale stability studies, whether using a generic model such as that discussed here, or detailed user-written vendor specific models, one thing is for certain and that is we cannot predict with much accuracy what the wind-speed and rotor-speed of each wind turbine in a wind power plant (WPP) is going to be for a future scenario. Furthermore, the accepted practice for modeling WPPs in large scale stability studies is by using an aggregated WTG model with a simple feeder model. Thus, it is not feasible to model such details even if such data were available. In short, the simple IBFFR model applied on an aggregated WPP model cannot be made to emulate exactly what actual field response will be due to the stochastic nature of the resource. As such, we are in need of a simplifying assumption to make the model usable. Although clearly not representative of what would happen in the field, the most conducive assumption is to assume that all the WTGs in the WPP are at the same power level and experiencing the same wind speed. That is how things were modeled here, and as seen the results are reasonable, but not perfect, as expected.

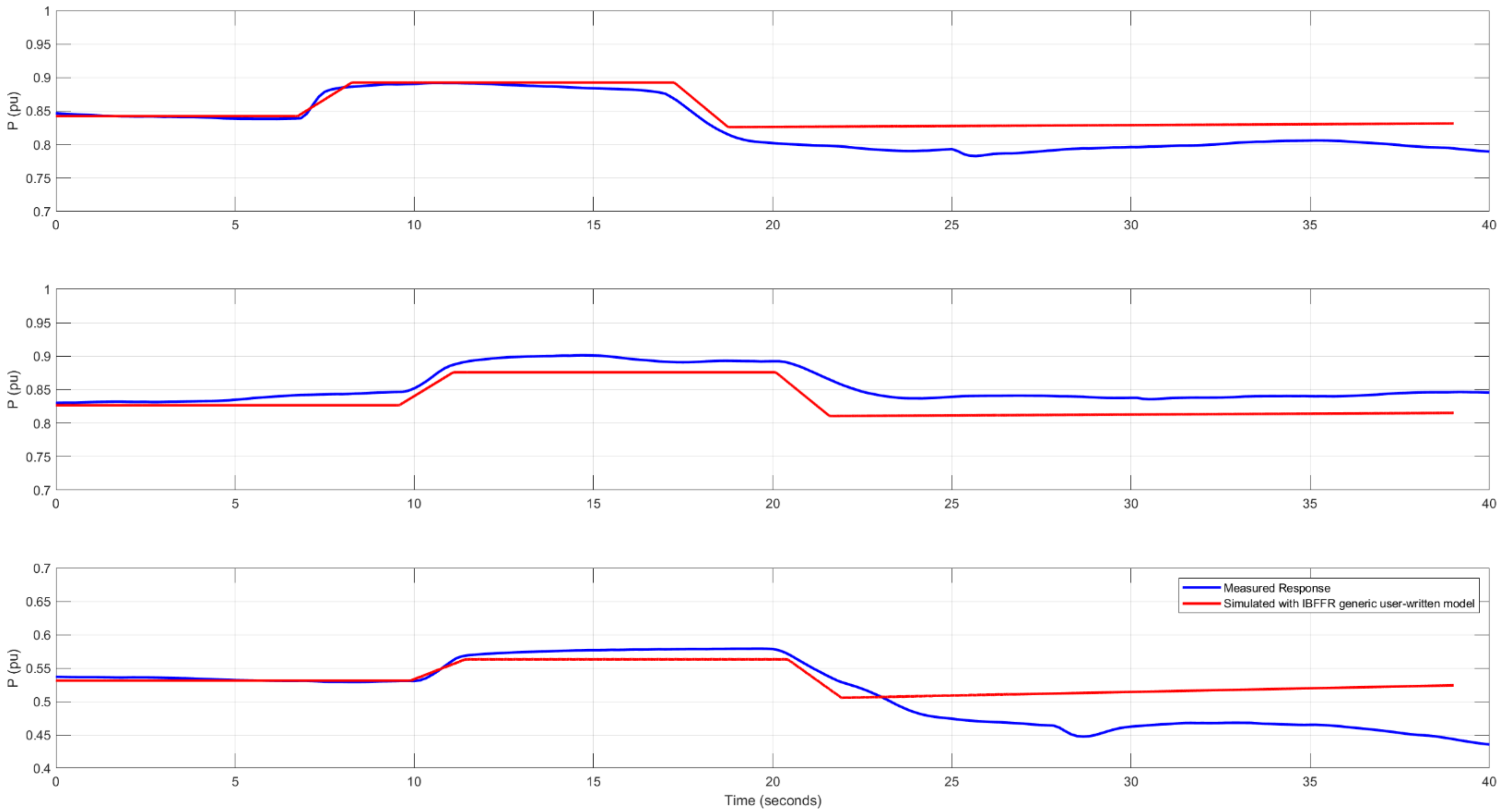

Figure 3-2
Simulation results as compared to actual measured response of a large WPP related to the emulated inertial response.

4
CONCLUSION AND SUMMARY

This document provides a concise description of the concept of inertial-based fast-frequency response, which is offered by many wind turbine generator manufacturers as an add-on supplemental feature. In addition, a simple generic model was specified for emulating this feature for power system stability simulations in the work done in 2018, and that model structure is briefly presented here again for completeness. The simple model has been shared publicly with the Western Electricity Coordinating Council's Modeling and Validation Working Group (WECC MVWG) at its November 2018. In this report we present results of comparing the performance of this simple model with field measured inertial-based fast-frequency response of an actual wind power plant. It is thus shown that the model can reasonably emulate the actual observed behavior of a wind power plant. It is therefore hoped that the model will now be accepted by WECC and adopted by the major commercial software vendors in North America and then perhaps in 2020, a beta version of the model may become available in the major commercial tools, and it can then be tested and verified for official release.

5
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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
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