Recent efforts of the WECC REMTF have resulted in development of the now so-called second-generation generic renewable energy system (RES) models [1] and [2]. These models were first released in the major commercial software platforms in 2014. Since that time adoption of these models has been gradually increasing. WECC started adopting the models in late 2014, early 2015, and by this time the vast majority of the first-generation generic models have been replaced in the WECC database. Adoption of these models in the Eastern Interconnection has been slower.

As with any model development process there needs always to be a balance between perfection and timely development for application to yield value. Thus, the initial development of the second-generation RES models started wholesale in late 2010/early 2011, within the WECC REMTF, and culminated in January 2014. It is now time to revisit the models and propose modifications to further improve their applicability. At the last two WECC MVWG meetings, with input from several of the major equipment vendors and other stakeholders, discussions have ensued to propose new features and additions to the models. Given the modular nature of the second-generation RES models, these proposed changes can be readily adopted through the implementation of a new set of modules to be added to the RES model library.

In parallel to the efforts of WECC REMTF, and in collaboration in the early stages of both efforts, the IEC TC88 WG27 has been developing international standard specifications for generic wind turbine generator models since 2010. The first stage of that work, which was focused on the individual wind turbine generator, was completed in September 2016. The remaining work, the development of plant level controllers, is not yet complete.

With the above background, this document presents the collection of proposed additions/changes to the 2nd generation RES models developed in WECC, based on input from several vendors and discussions at the most recent WECC REMTF meetings. With respect to the proposed new inertia-based fast-frequency-response (IBFFR) model, the presentation here is our initial proposal based on an understanding of the general nature of these controls, it is not by any means an exact representation of any vendors equipment. In general, this is true of all the model modifications presented. These so-called generic models are able to reasonably “emulate” the behavior of equipment, if parameterized appropriately.

**Revision Note:**

The original version of this memo was circulated publicly to the forums listed above, and discussed at length on a WECC REMTF webcast/call on 9/6/18. Furthermore, a subsequent revision was discussed at the WECC MVWG meeting in Salt Lake City, UT on November 28th, 2018. Thus, this revision includes comments received from many of the various stakeholders during both the webcast/call on 9/6/18 and the MVWG meeting on 11/28/18. This includes comments from several major wind and solar PV vendors (First Solar, GE, Senvion, Siemens-Gamesa, and Vestas), as well as the major commercial software vendors for power system simulation tools (GE, PowerWorld, PowerTech Labs, Siemens PTI). The input from all these entities, WECC REMTF members, and EPRI are most gratefully acknowledged.
One of the key outcomes of the 11/28/18 MVWG meeting was a prioritization of the implementation of the proposed new modules in this memo. The agreed to prioritization is as follows:

1. REGC_B
2. REEC_D

(as of August 14, 2019, beta versions of the above two models have been developed in the four North American commercial tools and testing should start soon)

3. REPC_C & WGO – to hopefully be developed as a beta version by the November 2019 meeting
4. WTGP_B, WTGT_B, WTGQ_B & IBFFR – to hopefully be developed as a beta version by early 2020
5. REGC_C – to be developed hopefully as a beta by Q2 in 2020

1.0 Overview:
The RES models are composed of four (4) categories of modules [1] and [2]:

1. The renewable energy generator-converter models (REGC_*)
2. The renewable energy electrical-control models (REEC_*)
3. The renewable energy plant-controller models (REPC_*)
4. The mechanical and aero-dynamic models associated with wind turbine generators

New features or modifications have been proposed in all the above categories. Here the most significant of these, which in principle have been agreed to in the recent WECC REMTF meetings, will be described. It should be noted that work continues with respect to some other modification that are only mentioned here, but not described in detail, since they will be forthcoming in other presentations once finalized.

In addition to the above, in this document, we are proposing the introduction of a new class of modules which we will call “auxiliary controls”. In this category will fit at present two (2) new models being proposed, that have been under discussion in the WECC MVWG for some time

2.0 Generator/Converter Models:
Presently, the only available REGC model is the REGC_A model (see [1] or [2]) which is a simple current-source model. The main limitation of this model is numerical stability when applied for modeling RESs connected to a relatively weak grid node. There are numerical tricks that can be played to extend its use (e.g. shortening integration time steps, etc.), however, none of this is truly conducive. Thus, several proposals have been put forth for new REGC models to extend the range of applicability of the REGC models. These proposals are as follows:

2.1 REGC_B (new model)
This is an extension of the REGC_A model by changing the network interface between the generator/converter model from a current-source to a voltage-source, based on [3].
Figure 1: REGC_B model

The above figure defines the REGC_B model. The reactive-current arm is identical to REGC_A. The interface to the grid is a simple voltage-source, based on [3]. The active-current arm, as presented here, is significantly different to REGC_A and hitherto not presented in the form shown in Figure 1. The changes, and the reasoning behind the changes are as follows:

- The new flag $\text{RateFlag}$ allows the user to make the effect of the rate limit for the increase in active-current ($\text{rrpwr}$) to be either a rate-limit in active-current (by setting $\text{RateFlag} = 0$) or active-power (by setting $\text{RateFlag} = 1$). This is because some vendors have indicated that the rate limit is implemented in their controls as an active-power rate limit.

- The lag block ($\text{Tfltr}$) allows for modeling of a small delay in the measurement of terminal voltage ($\text{Vt}$). $\text{Tfltr}$ can be set to zero.

- The hardcoded lower limit on the voltage measurement lag block (0.01) is implemented to prevent a divide by zero. The limit must be effected even if $\text{Tfltr} = 0$. Also, the limit should be on $\text{Vt}$ (as shown) and not on only the division arm, so that the same value of $\text{Vt}$ is first multiplied by $\text{Ipcmd}$ and then later $\text{Ipcmd}$ is divided by the same number.

- The LVPL block and associated parameters (used in REGC_A – see [1]) has been completely removed. The reasoning is as follows:
  - This block is typically only used by a few vendors
  - With the extended VDL blocks (see below section 3), we believe that the function of the LVPL block can be easily emulated with the VDL2 block and thus it is not necessary and would add confusion (and based on many questions from users, the LVPL function already does cause confusion).
  - However, once REGC_B is implemented and tested, if some vendors find that it is absolutely necessary to re-introduce the block, that will be considered. This remains to be seen.

- Current Limits: during the network solution, at the interface of the model, based on discussions within the group, it was concluded that some sort of current limits might be useful in order to minimize the potential for current spikes due to numerical issues. It should be understood, that there are no “current limits” applied in reality at physical interface of the inverter to the grid. All such limits are
applied in the controls (REEC_* models). The reason for introducing this algebraic manipulation at the network interface is to help to mitigate some of the un-realistic current spikes often seen in the RMS models. For a detailed explanation of the implementation that was developed by EPRI see [9]. EPRI [4] has demonstrated the potential benefit of this algebraic manipulation at the network interface. This will need further discussion and investigation once a beta version of the model is available for testing in the commercial tools to assess the efficacy of these limits. The $Imax$ and $pqflag$ parameters below are the maximum current limit and P/Q priority settings on the converter (these values should be consistent with the associated REEC_* model), which is to be used for applying this limit in the network solution iterations.

- The ramp-rate of recovery after a fault on active-current ($rrpwr$) should also be imposed (in the opposite direction) when the model is being used to “emulate” charging of an energy storage device. That is, when $P_{gen}$ is negative, then $rrpwr$ should have its sign changed and it becomes the ramp-rate at which charging power (power being absorbed by the model) increases after a fault$^1$.

Table 1: Parameter List for REGC_B

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_g$</td>
<td>Emulated delay in converter controls [s] (Cannot be zero)</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>$I_{qmax}$</td>
<td>Rate at which reactive current recovers after a fault when the initial reactive power output ($Q_{geno}$) of the unit is greater than zero (typically disabled by setting to 999) [pu/s]</td>
<td>1 – 999</td>
</tr>
<tr>
<td>$I_{qmin}$</td>
<td>Rate at which reactive current recovers after a fault when the initial reactive power output ($Q_{geno}$) of the unit is less than zero (typically disabled by setting to -999) [pu/s]</td>
<td>-1 – -999</td>
</tr>
<tr>
<td>$T_{fltr}$</td>
<td>Filter time constant for voltage measurement. Can be set to “auto”. [s]</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>$rrpwr$</td>
<td>Rate at which active current (power) recovers after a fault [pu/s]</td>
<td>1 – 20</td>
</tr>
<tr>
<td>$RateFlag$</td>
<td>0 – $rrpwr$ represents active-current ramp rate; 1 – $rrpwr$ represents active-power ramp rate</td>
<td>N/A (if in doubt set to 0)</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Emulated delay in converter controls [s] (Cannot be zero)</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>$Imax$</td>
<td>Maximum current rating of the converter [pu]</td>
<td>1.1 – 1.4</td>
</tr>
<tr>
<td>$pqflag$</td>
<td>1 – P priority and 0 – Q priority on the current limits</td>
<td>N/A</td>
</tr>
<tr>
<td>$re$</td>
<td>Source resistance [pu]; typically set to 0</td>
<td>0 – 0.01</td>
</tr>
<tr>
<td>$X_e$</td>
<td>Source reactance [pu]</td>
<td>0.05 – 0.2</td>
</tr>
</tbody>
</table>

2.2 REGC_C (new model)

Another more complicated proposal for a generator/converter model is an alternative to REGC_B which EPRI has been working on and presented at the last WECC MVWG meeting [4]. The core difference between what is presented in [4] and the REGC_B model shown above is the following:

1. The addition of a simplified phase-lock loop (PLL) model (blocks associated with $K_{ppll}$, $K_{ipll}$), based on the attempt that was made in the 1st generation generic models for wind turbine generators (see https://www.esig.energy/wiki-main-page/wt3-generic-wind-model/), and

---

$^1$ A simple way to model this is:

If $ds1/dt$ (derivative of state 1) > +$rrpwr$ then
If $s1$ > 0 then $ds1/dt$ = +$rrpwr$
Elseif $ds1/dt$ < -$rrpwr$ then
Else if $s1$ <= 0 then $ds1/dt$ = -$rrpwr$
EndIf
This is checked at every-time step.
The addition of a simplified representation of the inner-current control loops (PI controllers with gains $K_{ip}, K_{ii}$) – this has not been attempted previously in the generic models. Based on the results shown in [4] we believe it is clear that the combination of the PLL, inner-current control loops and the voltage-source representation in REGC_B does collectively present some potential additional fidelity and usefulness for extending the range of applicability of the generic models. Here the block diagram presented below combines the concepts presented in [4], together with the changes presented above in REGC_B to propose a so-called REGC_C model.

Note that the purpose of the Imax and pqflag parameters are introduced here for the same reason as in REGC_B, to be used for imposing the maximum current limit during network solution iterations (see [9]).

![Figure 2: REGC_C model](image)

**Figure 2**: REGC_C model. The block $T^{-1}$ represents the reference frame transformation between the network and controls. Details of the network solution iterations are not shown that are discussed in [4]. This model still requires some further investigation and fine tuning. What is presented here in Figure 2 is slightly different from that in [4], in that it introduces some of the new features of REGC_B presented above.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{qrmax}$</td>
<td>Rate at which reactive current recovers after a fault when the initial reactive power output ($Q_{geno}$) of the unit is greater than zero (typically disabled by setting to 999) [pu/s]</td>
<td>1 – 999</td>
</tr>
<tr>
<td>$I_{qrmin}$</td>
<td>Rate at which reactive current recovers after a fault when the initial reactive power output ($Q_{geno}$) of the unit is less than zero (typically disabled by setting to -999) [pu/s]</td>
<td>-1 – -999</td>
</tr>
<tr>
<td>$T_{fltr}$</td>
<td>Filter time constant for voltage measurement. Can be set to “zero”. [s]</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>$r_{pwr}$</td>
<td>Rate at which active current (power) recovers after a fault [pu/s]</td>
<td>1 – 20</td>
</tr>
</tbody>
</table>

2 This is a very simplified diagram; the details can be obtained in EPRI’s presentation reference [4].
3 See implementation of $r_{pwr}$ for REGC_B on page 4.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>( RateFlag )</td>
<td>0 – ( rrpw ) represents active-current ramp rate; 1 – ( rrpw ) represents active-power ramp rate</td>
<td>N/A</td>
<td>(if in doubt set to 0)</td>
</tr>
<tr>
<td>( Imax )</td>
<td>Maximum current rating of the converter [pu]</td>
<td>1.1 – 1.4</td>
<td></td>
</tr>
<tr>
<td>( pqflag )</td>
<td>1 – ( P ) priority and 0 – ( Q ) priority on the current limits</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>( Te )</td>
<td>Emulated delay in converter controls [s] (Cannot be zero)</td>
<td>0.02 – 0.05</td>
<td></td>
</tr>
<tr>
<td>( r )</td>
<td>Source resistance [pu]; typically set to 0</td>
<td>0 – 0.01</td>
<td></td>
</tr>
<tr>
<td>( Xe )</td>
<td>Source reactance [pu]</td>
<td>0.05 – 0.2</td>
<td></td>
</tr>
<tr>
<td>( Kp )</td>
<td>Proportional-gain of the inner-current control loop [pu/pu]</td>
<td>1 – 10 (to be discussed)</td>
<td></td>
</tr>
<tr>
<td>( Ki )</td>
<td>Integral-gain of the inner-current control loop [pu/pu.s]</td>
<td>20 – 100 (to be discussed)</td>
<td></td>
</tr>
<tr>
<td>( Kppil )</td>
<td>Proportional-gain of the PLL [rad.s/pu]</td>
<td>1 – 10 (to be discussed)</td>
<td></td>
</tr>
<tr>
<td>( Kpil )</td>
<td>Integral-gain of the PLL [rad.s/pu.s]</td>
<td>500 – 3000 (to be discussed)</td>
<td></td>
</tr>
<tr>
<td>( wmax )</td>
<td>Upper limit on the PLL [rad.s]</td>
<td>To be discussed</td>
<td></td>
</tr>
<tr>
<td>( wmin )</td>
<td>Lower limit on the PLL [rad.s]</td>
<td>To be discussed</td>
<td></td>
</tr>
</tbody>
</table>

### 2.3 IEC TC88 WG27 Modules

There are two other models specifically for type 3 WTG generator/converters, that would fall under this same category of the REGC models which have been proposed by the IEC TC88 WG27 group in the recently published IEC standard CDV, which will hopefully soon be approved. They are called the “type3A” and “type3B” models in the IEC Standard document. Here we could call them for example, \texttt{REGC_IEC3A} and \texttt{REGC_IEC3B}. Consideration should be given to adopting those models when the IEC standard is finalized. They include items such as the active-crow bar emulation\(^4\), which was previously investigated also by the WECC MVWG but not adopted.

In addition, there is a second more complex aero-dynamics model proposed in the IEC standard, which may be useful to have implemented in order to have it available in the mix of models.

\(^4\) An early presentation of the active-crow bar simulation was presented in section 5 of \url{https://www.wecc.biz/Reliability/WECC-Type-3-Wind-Turbine-Generator-Model-Phase-II-012314.pdf} but at the time not adopted by WECC due to its complexity.
3.0 Electrical Control Models:

Presently, there are three (3) existing REEC_* models (see [2]):

1. **REEC_A**: the most commonly used model for both wind and PV plants.
2. **REEC_B**: a simplified version of the electrical controls, which was previously used for PV plants but is no longer recommended (originally proposed in [5]).
3. **REEC_C**: a model intended primarily for use in modeling energy storage systems.

As indicated above, the REEC_B model is no longer recommended for use in most cases since it is devoid of the ability to represent the voltage-dependent limits (VDL) on the inverter current. The REEC_A and REEC_C models, although quite comprehensive, and though both do include the VDL tables, there are some improvements that have been pointed out by several vendors recently, including Siemens-Gamesa, Vestas and Senvion. Here those suggested improvements have been collected into a new proposed model – REEC_D.

3.1 **REEC_D** (new model)

The REEC_D (Figure 3) model is identical to the REEC_A model, with the following additions/modifications:

1. **The VDL tables in REEC_D should have ten (10) pairs of points**: That is,
   a. VDL_q reactive-current limits = \{(iq_1, vq_1), (iq_2, vq_2), (iq_3, vq_3), (iq_4, vq_4), (iq_5, vq_5), (iq_6, vq_6), (iq_7, vq_7), (iq_8, vq_8), (iq_9, vq_9), (iq_10, vq_10)\} 
   b. VDL_p active-current limits = \{(ip_1, vp_1), (ip_2, vp_2), (ip_3, vp_3), (ip_4, vp_4), (ip_5, vp_5), (ip_6, vp_6), (ip_7, vp_7), (ip_8, vp_8), (ip_9, vp_9), (ip_10, vp_10)\}

   The iq’s can be positive or negative.
   The ip’s must all be greater than or equal to zero.

   Furthermore,

   If (Pqflag = 0) (i.e. Q – priority)
   \[ I_{q_{max}} = \min \{VDL_q, Imax\} \]
   If \(I_{q_{max}} < 0\)
   \[ I_{q_{min}} = I_{q_{max}} \text{ (important new logic)} \]
   else
   \[ I_{q_{min}} = -1 \times I_{q_{max}} \]
   end

   \[ I_{p_{max}} = \min \{VDL_p, \sqrt{Imax^2 - Iq_{cmd}^2}\} \]
   \[ I_{p_{min}} = -Ke \times I_{p_{max}} \text{ (important new logic)} \]

   else (i.e. P – priority)

   \[ I_{q_{max}} = \min \{VDL_q, Imax\} \]
   \[ I_{q_{min}} = I_{q_{max}} \text{ (important new logic)} \]
   end

   \[ I_{p_{max}} = \min \{VDL_p, \sqrt{Imax^2 - Iq_{cmd}^2}\} \]
   \[ I_{p_{min}} = -Ke \times I_{p_{max}} \text{ (important new logic)} \]

   else (i.e. P – priority)


* It is important to note that all other aspects of REEC_A should be copied into REEC_D. What is presented here are only the suggested changes and additions.

7. Also, based on recommendations by some users, the names of the tables are to be changed from VDL1 and VDL2 to VDL_q and VDL_p, so that it is easier to identify which table is associated with reactive and active current, respectively.
\[ I_{q\text{max}} = \min \{ VDLq, \sqrt{I_{\text{max}}^2 - I_{\text{pcmd}}^2} \} \]

If \( I_{q\text{max}} < 0 \)

\[ I_{q\text{min}} = I_{q\text{max}} \text{ (important new logic)} \]

else

\[ I_{q\text{min}} = -1 \times I_{q\text{max}} \]

end

\[ I_{p\text{max}} = \min \{ VDLp, I_{\text{max}} \} \]

\[ I_{p\text{min}} = -K_e \times I_{p\text{max}} \text{ (important new logic)} \]

end

The explanation for the new logic (marked in blue comments) above is as follows:

- If \( K_e = 0 \), then the model mimics a generator, that is \( I_{p\text{min}} = 0 \) and the unit cannot absorb active power from the grid (see Figure 4).
- If \((1 \geq K_e > 0)\), then the model mimics a storage device, that is capable of also absorbing active current. A value of \( K_e < 1 \) implies that the device has a lower capacity for absorbing instantaneous power, as compared to its capacity of generating instantaneous power (see Figure 5).
- \( K_e \) cannot be negative or greater than 1.
- In the case that \( I_{q\text{max}} \) is negative, then \( I_{q\text{min}} \) must also be negative and the same value in order to force \( I_{\text{cmd}} \) to this limit. This is used in some cases during extreme high voltages to make the inverter absorb reactive power (see Figure 6).

2. The addition of two new blocks:

a. A local current-compensation block \( (|Vt – (rc + j Xc).It|) \) with a lag block to emulate measurement delays \( (T_{rf}) \). The lag block time-constant \( (T_{rf}) \) can be set to zero. Likewise, \( rc/Xc \) can both be set to zero to eliminate modeling of current-compensation. The inputs to this block are the terminal-voltage \( (Vt) \) of the generator/converter model (REGC_*) which is downstream of this model, and the terminal-current \( (It) \) of the same. Both these values \( (Vt \) and \( It) \) are the complex \( (real + j.imaginary) \) values of voltage and current.

b. A local reactive-droop compensation block \( (Kc) \) with a lag block to emulate measurement delays \( (T_{rf}) \). The lag block time-constant \( (T_{rf}) \) can be set to zero. Likewise, \( Kc \) can be set to zero to eliminate modeling of reactive-current compensation. The input to this block is the terminal generated reactive-power \( (Q_{gen}) \) voltage of the generator/converter model (REGC_*) which is downstream of this model.

c. The reactive-current injection arm (which has the output \( I_{q\text{inj}} \)), is slightly different in this model, as compared to REEC_A. First, the logic around the switch at the output of this arm has been completely removed. This arm is always active (as long as \( Kqv \) is non-zero). To completely disable this arm, \( Kqv \) can be set to zero and \( Vdip/Vup \) set to e.g. -1 and 2 to completely turn-off the voltage-dip logic. The two parameters \( I_{q\text{frz}} \) and \( Thld \) remain, but now have a slightly different function. The logic is as follows:

i. If \( Thld = 0 \) – no other action is taken.

ii. If \( Thld > 0 \), then for \( Thld \) seconds following a voltage dip (i.e. \( voltage_{\text{dip}} \) goes from 1 back to 0) \( I_{\text{cmd_bl}} \) is held at its current value (i.e. value just prior to the end of the \( voltage_{\text{dip}} \)) for \( Thld \) seconds and is then released.
iii. If $Thld < 0$, then for $Thld$ seconds following a voltage dip (i.e., voltage dip goes from 1 back to 0) $Ip_{cmd}$ is held equal to $Iq_{frz}$ for $Thld$ seconds and is then released.

**Note:** The value of $Iq_{cmd}$ that is held/frozen is the value that is after the summing junction and just before the $Iq_{max}/Iq_{min}$ limits as shown in Figure 3. The purpose of this feature is primarily to help with better modeling of momentary cessation.

The REEC_D has the same logic as in REEC_A that holds/freezes active current command at the previous value for $Thld$ seconds following a voltage dip, i.e. voltage dip goes from 1 back to 0.

3. Blocking Logic: At very low voltages at the terminals of the converter the converter power electronic will block. In recent work within NERC and WECC this has been referred to as momentary cessation. A detailed discussion of this subject is outside of the scope of this document. Although it may be possible to model inverter blocking by properly parameterizing the VDI tables and the $Thld$ and $Thld2$ parameters, this may not be entirely desirable since those parameters are more typically used for modeling the voltage dependence of the inverter current limits and the voltage-dip logic, which can be independent of blocking. Thus, the following three new parameters are proposed to be completely independent of all the other parameters and to be used for modeling converter blocking:

a. $vblkl$ – this is the voltage below which the converter will block, that is if the measured terminal voltage of the generating device (Vt_filt in Figure 3, i.e. state S0) is less than or equal to $vblkl$ then $Iq_{cmd}$ and $Iq_{frz}$ are forced to 0 (i.e. $Iq_{cmd} = Iq_{max} = Iq_{min} = Ip_{max} = 0$ and thus both the $Ip_{cmd}$ and $Ip_{frz}$ = 0).

b. $vblkh$ – this is the voltage above which the converter will block, that is if the measured terminal voltage of the generating device (Vt_filt in Figure 3, i.e. state S0) is greater than or equal to $vblkh$ then $Iq_{cmd}$ and $Iq_{frz}$ are forced to 0 (i.e. $Iq_{cmd} = Iq_{max} = Iq_{min} = Ip_{max} = 0$, and thus both the $Ip_{cmd}$ and $Ip_{frz}$ = 0).

c. $Tblk_{delay}$ – once the converter comes out of the blocking mode (i.e. voltage recovers after a blocking incident back within the range of $vblkl < Vt_{filt} < vblkh$) the current limits are released only after $Tblk_{delay}$ seconds (i.e. $Iq_{cmd} = Iq_{max} = Iq_{min} = Ip_{max} = 0$ for another $Tblk_{delay}$ seconds after the voltage recovers outside of the blocking range).

3.4. The non-wind up limits: The non-wind up limits shown on the two PI controllers in the REEC_* models can be implemented several different ways, all of which are legitimate non-winding limit representations, but which will yield subtly different results for extreme cases that force the controllers into their limits. Based on a discussion as to how to attempt to harmonize the performance of these models across the various commercial software platforms, here we present one way of implementing the non-windup limits, which all software vendors can adopt, if they wish, to make the implementation uniform. This can be adopted for REEC_D. However, this discussion among the software vendors, rightfully so, identified one key challenge with trying to do this: if all software vendors implement the exact same form of the non-windup limit (as shown below) in REEC_D and yet this implementation is not the same as was used by the software vendors in previous models (e.g. REEC_C, REEC_A, etc.), then users may complain about inconsistency of results, even if subtle, when going from one model to the other with all the same parameters.

Some of the vendors are actually already using the approach shown below, or something quite similar. Thus, in the end we have no choice but to leave the exact implementation of the non-windup limits to the judgement and discretion of each software vendor.

Here an example way of implementing a non-windup limit is given. Consider the PI controller associated with state 3, it could be implemented as follows:

\[ ds3 = Kei \times errr \]
\[ \text{if } (s3 \geq Iq_{max}) \]
\[ s3 = Iq_{max} \]
elseif (s3 ≤ Iqmin)
  s3 = Iqmin
end
if ((s3 ≥ Iqmax) and (ds3 > 0))
  ds3 = 0
elseif ((s3 ≤ Iqmin) and (ds3 < 0))
  ds3 = 0
end
PI = s3 + Kvp × error
if (PI ≥ Iqmax)
  PI = Iqmax
elseif (PI ≤ Iqmin)
  PI = Iqmin
end

where error is the input to the PI block (i.e. the output of the summing junction which is going into the PI block), PI is the total output of the PI block, ds3 is the derivative of the integrator, and s3 is the state (output) of the integrator.

Further to the above, for these two PI blocks a special additional requirement is (see footnote on page 3-6 of [1]), that the non-windup integrators for s3 and s2 are linked. This link is as follows: if s3 hits its maximum limit and ds3 is positive, then ds3 is set to 0 (as shown in the pseudo code above), and further more if ds2 is also positive, then it is also set to 0 to prevent windup, but, if ds2 is negative, then ds2 is not set to 0. A similar rule is applied for s3 hitting the lower limit, but the check is whether ds3 and ds2 are negative.

4.5. The addition of $P_{aux}$: The new input $P_{aux}$ should be accessible both by the user for manipulation by an external user-written model, or by the auxiliary control models discussed below in section 6.0.

5.6. Filter Time Constant: Note that now voltage dip is determined from the filtered ($V_{t,filt}$) voltage rather than $V_{t}$.

Apart from the above additions/changes all other aspects of this model are identical to REEC_A. Thus, the software vendors may start with the code for REEC_A and make the above changes to get to REEC_D.

Important Note: all input references (i.e. $V_{ref}$, $p_{faref}$, $V_{ref1}$, $P_{ref}$, $Q_{ext}$ and $P_{aux}$) should be accessible to the user after model initialization such that they can be either step-changed or controlled by an external user-written model. Clearly, if this model is connected to one of the standard plant controller models (rep*) then $Q_{ext}$ and $P_{ref}$ will be controlled by that model and cannot be also controlled by another user-written model.
Figure 3: REEC_D model.
Table 3: Parameter List for REEC_D – only new additional parameters are listed here; all other parameters are identical to REEC_A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value(^9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n)</td>
<td>Current-compensation resistance [pu]</td>
<td>0 – 0.02</td>
</tr>
<tr>
<td>(Xc)</td>
<td>Current-compensation reactance [pu]</td>
<td>0.01 – 0.12</td>
</tr>
<tr>
<td>(T)</td>
<td>Filter time constant for voltage measurement. Can be set to “zero”. [s]</td>
<td>0.02 – 0.05</td>
</tr>
<tr>
<td>(Kc)</td>
<td>Reactive-current compensation gain</td>
<td>0.01 – 0.05 (to be discussed)</td>
</tr>
<tr>
<td>(V_{inpflag})</td>
<td>1 – use current compensation, 0 – use reactive droop</td>
<td>N/A</td>
</tr>
<tr>
<td>(Ke)</td>
<td>Scaling on Ipmin; set to 0 for a generator, set to a value between 0 and 1 for a storage device, as appropriate</td>
<td>0 – 1</td>
</tr>
<tr>
<td>(Iqfrz)</td>
<td>Value to which reactive-current command is frozen after a voltage-dip [pu]</td>
<td>0</td>
</tr>
<tr>
<td>(Thld)</td>
<td>Time for which reactive-current command is frozen after a voltage-dip [s]; if positive then (Iqcmd) is frozen to its final value during the voltage-dip; if negative then (Iqcmd) is frozen to (Iqfrz)</td>
<td>0</td>
</tr>
<tr>
<td>(VDL,q)</td>
<td>10 pairs of values defining the voltage dependent reactive-current limits [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>(VDL,p)</td>
<td>10 pairs of values defining the voltage dependent active-current limits [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>(q)</td>
<td>The maximum value of the incoming Qext or Vext [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>(qmin)</td>
<td>The minimum value of the incoming Qext or Vext [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>(vblkl)</td>
<td>Voltage below which the converter is blocked (i.e. (Iq = Ip = 0))</td>
<td>N/A</td>
</tr>
<tr>
<td>(vblkh)</td>
<td>Voltage above which the converter is blocked (i.e. (Iq = Ip = 0))</td>
<td>N/A</td>
</tr>
<tr>
<td>(Tblk)</td>
<td>The time delay following blocking of the converter after which the converter is released from being blocked</td>
<td>0.04 – 0.1</td>
</tr>
</tbody>
</table>

**Important Note:** note that the position of \(qmax\)/\(qmin\) is different to previous versions of the REEC_* models. It is now being applied on any incoming signal from the plant controller, or power factor control, regardless of the chosen flags within REEC_D.

---

\(^9\) The typical range of values here are a preliminary set of values discussed briefly with several vendors. They are to be further discussed and verified with the vendors once the model is implemented.
Figure 4: Example of VDL_p table with $K_\tau = 0$.

Figure 5: Example of VDL_p table with $K_\tau = 0.5$ to emulate a storage system which can charge at a maximum charging current of half as much as the maximum discharging current.

Figure 6: Example of VDL_q table.
4.0 Plant Controller Models

4.1 REPC_C (new model)

This proposed new plant-controller model is based off of the existing REPC_A model, which interfaces to a single aggregated WTG model. These same changes may also be applied to the REPC_B model to create a second complex plant controller – whether that is needed should be further discussed at the next WECC MVWG meeting.

The REPC_C model is identical to the REPC_A model, with the following additions/modifications (see Figure 7):

1. **Limits on Vref and Qref**: Adding max/min limits on the Vref and Qref input signals.
2. **Auxiliary Inputs**: Adding a Vaux and Paux signal to the voltage and power reference summing junctions, which can be accessed through programing by the user to implemented user-written auxiliary controls.
3. **Measurement Time Constants**: The measurement time-constant (Tfltr) is added also to the Vref signal, and it has been moved for the current-compensation block. Also, a separate measurement delay time-constant (Tc) has been added to the reactive-current compensation block and frequency measurement (Tfrq).
4. **Rate Limits**: Rate limits have been added to Qref (dqrefmax/dqrefmin), Plant Pref (dprmax/dprmin), the power factor reference (dpfmax/dpfmin) and the output of the reactive-power command signal (qvrmax/qvrmin). The rate limits on the reactive-power command (qvrmax/qvrmin) should be disabled (e.g. set to 9999/-9999) when the plant controller is producing a voltage signal (Vext). The model should determine automatically, upon initialization, whether the output (Qext/Vext) is a Q-command or V-command, depending on the downstream rec_* model.
5. **Power Factor Control**: Adding the functionality of power factor control at the plant level. The constant pfaref is not a user entered value. Upon initialization, pfaref is internally calculated by the program to be tan⁻¹(Qbranch/Pbranch), where here the values of Q branch and P branch are the initial values of these variables at time = 0 in the simulation.
6. **A feedforward path in the frequency control**: A new feedforward path can be introduced by setting the flag Ffwrd_flag = 1. See the special instructions (yellow high-lighted box in Figure 7) on how this flag is to be utilized. This is used by some vendors and should be used with specific information from the vendor. When the Ffwrd_flag is used, the values of pimax/pimin may be set differently to Pmax/Pmin.
7. **Coordinated Switching of Shunt Capacitors and Reactors**: The logic for coordinated switching of mechanically switched shunts (MSS) has been added. This logic is copied from the generic SVS models [6]. For completeness, the switching logic is depicted in Figure 8. There are eight (8) parameters associated with the switching logic. The four reactive thresholds at which switching occurs (Qdn1, Qdn2, Qup1, Qup2), the two-time delays for switching (Tdelay1 and Tdelay2), the time delays associated with the opening/closing of the MSS breaker (Tmssbrk), and the discharging time of the shunt capacitors (Tout). For more details see [6] or the logic of any of the SVS models (SVSMO1, SVSMO2, and SVSMO3). In addition, each shunt capacitor/reactor that is to be controlled by this plant controller in the power flow case, during time-domain stability simulations, must also be associated with generator on which the REPC_C model is instantiated. As an example, for the SVSMO* models this is done in GE PSLF™ by specifying the bus number and ID of the SVS device that is controlling the shunt in the shunt data record. The same approach could be used here. For now, we will assume that no more than ten (10) MSSs are to be controlled by a plant controller.
8. **Freezing of both Active and Reactive Power Output**: the states s2, s3, s5 and s6 are all frozen if the filtered voltage (s7) falls below Vfrz. Furthermore, once the filtered voltage recovers above Vfrz, these states remain frozen for another Tfrz seconds (which can be 0). This delay has been introduced to
allow coordination with the downstream inverter/turbine models such that the freeze remains until the inverter level LVRT actions have been completed. Furthermore, the delay can be used to ensure that the plant level controls do not react to spikes in frequency or voltage caused by simulating a fault at the point-of-measurement (see https://www.wecc.biz/Reliability/WECC_White_Paper_Frequency_062618_Clean_Final.pdf). If Tfrz is none-zero the user must ensure that there is proper LVRT and voltage control actions at the inverter/turbine level controls and it is properly coordinated.
Figure 7: REPC_C model
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vrefmax</td>
<td>Maximum voltage reference [pu]</td>
<td>1.05 – 1.08</td>
</tr>
<tr>
<td>Vrefmin</td>
<td>Minimum voltage reference [pu]</td>
<td>0.95 – 1.0</td>
</tr>
<tr>
<td>Qrefmax</td>
<td>Maximum Q-reference [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>Qrefmin</td>
<td>Minimum Q-reference [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>dqrefmax</td>
<td>Maximum rate of increase of Q-reference [pu/s]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>dqrefmin</td>
<td>Maximum rate of decrease of Q-reference [pu/s]</td>
<td>N/A (set to -9999 to disable)</td>
</tr>
<tr>
<td>qvrmax</td>
<td>Maximum rate of increase of Qext (Vext) [pu/s]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>qvrmin</td>
<td>Maximum rate of decrease of Qext (Vext) [pu/s]</td>
<td>N/A (set to -9999 to disable)</td>
</tr>
<tr>
<td>dprmax</td>
<td>Maximum rate of increase of Plant Pref [pu/s]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>dprmin</td>
<td>Maximum rate of decrease of Plant Pref [pu/s]</td>
<td>N/A (set to -9999 to disable)</td>
</tr>
<tr>
<td>dpfmax</td>
<td>Maximum rate of increase of power factor [s⁻¹]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>dpfmin</td>
<td>Maximum rate of decrease of power factor [s⁻¹]</td>
<td>N/A (set to -9999 to disable)</td>
</tr>
<tr>
<td>Prmax</td>
<td>Maximum rate of increase of Pref [pu/s]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>Prmin</td>
<td>Maximum rate of decrease of Pref [pu/s]</td>
<td>N/A (set to 9999 to disable)</td>
</tr>
<tr>
<td>pinac</td>
<td>Maximum output of the active power PI controller [pu]</td>
<td>1.0</td>
</tr>
<tr>
<td>pinin</td>
<td>Minimum output of the active power PI controller [pu]</td>
<td>0.0</td>
</tr>
<tr>
<td>Pefd_flag</td>
<td>Enable (1) or disable (0) electrical power feedback</td>
<td>N/A</td>
</tr>
<tr>
<td>Tc</td>
<td>Reactive-current compensation time-constant [s]</td>
<td>0 – 2</td>
</tr>
<tr>
<td>Ffwd_flag</td>
<td>Feedforward flag (1) include feedforward and (0) disable</td>
<td>N/A</td>
</tr>
<tr>
<td>Qdn1</td>
<td>First stage of capacitor (reactor) switching out (in) [pu] – Qdn1 &lt; 0</td>
<td>N/A</td>
</tr>
<tr>
<td>Qdn2</td>
<td>Second stage of capacitor (reactor) switching out (in) [pu] – Qdn2 &lt; Qdn1</td>
<td>N/A</td>
</tr>
<tr>
<td>Qup1</td>
<td>First stage of capacitor (reactor) switching in (out) [pu] – Qup1 &gt; 0</td>
<td>N/A</td>
</tr>
<tr>
<td>Qup2</td>
<td>First stage of capacitor (reactor) switching in (out) [pu] – Qup2 &gt; Qup1</td>
<td>N/A</td>
</tr>
<tr>
<td>Tablay1</td>
<td>Time delay after which if Q &lt; Qdn1 (or Q &gt; Qup1) a capacitor (reactor) is switched [s]</td>
<td>N/A</td>
</tr>
<tr>
<td>Tablay2</td>
<td>Time delay after which if Q &lt; Qdn2 (or Q &gt; Qup2) a capacitor (reactor) is switched [s] – typically Tablay2 &lt; Tablay1</td>
<td>N/A</td>
</tr>
<tr>
<td>Tmslink</td>
<td>Time it takes to switch in (out) a mechanically switched shunt [s]</td>
<td>0.05 – 0.1 (set to zero to disable)</td>
</tr>
<tr>
<td>Tout</td>
<td>Time for discharging of a capacitor that has just been switched out; the same capacitor cannot be switched back in until Tout [s] has elapsed</td>
<td>typically, 120 – 300 seconds</td>
</tr>
<tr>
<td>Tfrz</td>
<td>A time delay during which the states (s2, s3, s5 and s6) are kept frozen even after the filtered voltage recovers above Vfrz. This can be used to ensure the plant controller does not interact with the inverter-level LVRT.</td>
<td>0 – 2 seconds</td>
</tr>
</tbody>
</table>
**Figure 8:** MSS switching logic

- **Inductive Vars**
  - **Qdn1**
  - **Qup1**
  - **Qup2**

- **Capacitive Vars**
  - **Qdn2**

- **Flowchart Details**
  - If $Q < Q_{dn1}$ for more than $T_{delay1}$ second, switch out Capacitor 1; return to **START**
  - If $Q > Q_{up1}$ for more than $T_{delay1}$ second, switch in Capacitor 1 (provided capacitor has been out for discharge time of $T_{out}$); return to **START**
  - If $Q < Q_{dn2}$ for more than $T_{delay2}$ second, switch out Capacitor 1; return to **START**
  - If $Q > Q_{up2}$ for more than $T_{delay1}$ second, switch in Capacitor 1 (provided capacitor has been out for discharge time of $T_{out}$); return to **START**
5.0 Changes to Mechanical Side Models for WTGs

5.1 WTGQ_B (new model)

These changes were proposed by Senvion some time ago, in 2015 or so. The changes are shown below in Figure 7. This is a proposed alternative torque controller model, which we shall call WTGQ_B.

Note: this model variation, as noted above, has been proposed by one vendor. Many within the WECC REMTF still have reservations as to its efficacy. It may need to be further tested as a beta model before final approval.

Figure 7: The WTGQ_B model

The intent of this model is that:

1. \( P_{ref} \) will always be no more than 1 pu (in some cases may go above 1 pu transiently, but cannot exceed \( P_{max} \), which at most is typically around 1.12 pu). Also, \( \omega_{ref} \), when power is at maximum is in the range of 1.2 to 1.3 pu (i.e. 120 to 130% of nominal system frequency), so \( T_{max} \) at maximum will be \( 1.12/1.2 = 0.93 \), and since in steady-state voltage should typically be 0.95 to 1.05 pu, then \( T_{max} \) will always be chosen to the \( P_{ref}/\omega_{ref} \), except when we have a voltage dip. This is the intent, and it does mean that with the use of this model the state \( s_2 \) is always saturated at its limit, even upon initialization.

2. Adding \( \omega \) when \( P_{ref} > P_{set} \) (typically around 0.9 pu) has a small transient effect following fault recovery, again this is intentional.

3. Finally, the minimum-select between \( V_t \) and \( P_{ref}/\omega_{ref} \) for setting \( T_{max} \) is intended to emulate roughly the fact that the state \( s_2 \) is reset to a value somewhat proportional to the size of the voltage dip upon fault clearing. Thus, when there is a voltage dip since \( s_2 \) is frozen during the dip (and the dip is determined by filtered voltage), then it will be set to a value equal to the value of \( V_t \) during the dip and start (be reset) from that value upon fault clearing.
Table 5: Parameter List for WTGQ_B – only new additional parameters are listed here; all other parameters are identical to WTGQ_A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w_0 )</td>
<td>Speed off-set [pu]</td>
<td>0 – 0.02</td>
</tr>
<tr>
<td>( P_{set} )</td>
<td>Power set-point [pu]</td>
<td>0.85 – 0.95</td>
</tr>
</tbody>
</table>
5.2 WTGP_B (new model)

Based on experience it has become clear that the pitch-controller model would benefit from the following modification, which is shown here as a proposed new model call WTGP_B (Figure 8). This is because in the actual controls the limits are often independent and thus in some simulation cases this can make a difference.

The difference between WTGP_B and the existing WTGP_A model is as follows:

1. The limits on the two integrators are now independent of the limits on the lag block (state s2). This provides for greater flexibility, which is often needed to emulate the behavior of the actual equipment.

2. The non-windup limits on s0 and s1 are to be implemented in the following way:

\[
\begin{align*}
\dot{s}_1 &= K_{ic} \times (P_{ord} - P_{ref}) \\
\text{if } (s_1 \geq \theta_{cmax}) & \quad s_1 = \theta_{cmax} \\
\text{elseif } (s_1 \leq \theta_{cmin}) & \quad s_1 = \theta_{cmin} \\
\text{else } & \quad s_1 = s_1 + \dot{s}_1 \\
\text{if } ((s_1 \geq \theta_{cmax}) \text{ and } (\dot{s}_1 > 0)) \text{ or } ((s_1 \leq \theta_{cmin}) \text{ and } (\dot{s}_1 < 0)) & \quad \dot{s}_1 = 0 \\
\text{elseif } ((s_1 \leq \theta_{cmin}) \text{ and } (\dot{s}_1 < 0)) \text{ or } ((s_1 \geq \theta_{cmax}) \text{ and } (\dot{s}_1 > 0)) & \quad \dot{s}_1 = 0 \\
\end{align*}
\]

and similarly, for s0. The point here is that the derivative of the state is set to zero when either s1 (s0) hits its own limits or the pitch-angle (s2) hits its limit.

Figure 8: The WTGP_B model
Table 6: Parameter List for WTGP_B – only new additional parameters are listed here; all other parameters are identical to WTGP_A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{max}}$</td>
<td>Maximum output of the pitch compensation controller [degrees]</td>
<td>20 – 30</td>
</tr>
<tr>
<td>$\theta_{\text{min}}$</td>
<td>Minimum output of the pitch compensation controller [degrees]</td>
<td>-5 – 0</td>
</tr>
<tr>
<td>$\theta_{\text{max}}$</td>
<td>Maximum output of the speed error controller [degrees]</td>
<td>20 – 30</td>
</tr>
<tr>
<td>$\theta_{\text{min}}$</td>
<td>Minimum output of the speed error controller [degrees]</td>
<td>-5 – 0</td>
</tr>
</tbody>
</table>

5.3 WTGT_B (new model)

This is a proposed new drive-train “emulation” model where the only input is the electrical power ($P_e$) of the generator and mechanical power ($P_m$) is simply taken to be a filtered value of $P_e$. This should ONLY be used with the type 4A (i.e. type 4 WTG with torsional emulation – see Figure 3-9 in the model specification for WTGs here: https://www.wecc.biz/Reliability/WECC-Second-Generation-Wind-Turbine-Models-012314.pdf). The idea is simple. When a type 4A WTG is modeled all the mechanical side models are neglected (i.e. pitch control, torque control, etc.). As such, in the wtgp_a model mechanical power ($P_m$) remains constant. This results in a net increase in speed after the simulation of a fault or other disturbance that momentarily decreased $P_e$ and thus a slight error in $P_e$ in steady-state once the fault clears. In real-life, following a disturbance, the change in turbine speed initiates the pitch control to adjust $P_m$ to bring the turbine back to its original steady-state speed and thus power. By doing what is shown in Figure 9, $P_m$ changes in a way that is similar (certainly not exactly the same) to the action of the pitch control following a disturbance in $P_e$. Thus, the steady-state error in $P_e$ does not occur. This is illustrated by a simple example simulation below.

---

*Note:* work done years ago showed that for a type 4 WTG, since the generator is fully decoupled from the grid, modeling all the mechanical elements provides little added fidelity for grid electrical response modeling - see https://www.wecc.biz/Reliability/WECC-Type-4-Wind-Turbine-Generator-Model-Phase-II-012313.pdf
Figure 9: The WTGT_B model
6.0 Proposed New Auxiliary Models

There has been discussion at several previous MVWG meetings about two additional modules, which we will call “auxiliary controls”. These modules apply only to wind turbine generators presently.

1. Weak-grid option controls
2. Inertia based Fast Frequency response

Below we describe these new proposed options, and we have also implemented them as simple user-written models and thus demonstrate their efficacy below in simple simulations.

6.1 WTGWGO_A (new model)

Some vendors (Siemens-Gamesa in particular) have indicated that in some cases they offer a supplemental control called a weak grid option (WGO). Here we present a simple generic model, as an auxiliary control which can be used to “emulate” this supplemental control. The model is shown in Figure 10. This auxiliary control would fit between the plant controller (REPC_) and the electrical controls model (REEC_). That is the Pref coming from the plant controller would go into Pref_in, and the output of this model, Pref_out, would go into the electrical controller for the WTG. For now, the intent is to have this model used only for type 4 WTGs – i.e. between REPC_* and REEC_*, as shown below. Once further testing is done with the model, it may be extended in the future to also interface between the WTGQ_* and REEC_* model for type 3 WTGs.

![Figure 10: The WTGWGO_A model, and how it fits into the sequence of RES models.](image)

The model can be explained as follows:

---

11 In the case of a type 3 WTG, if this model is used, the input (Pref_in) would come from the torque controller (WTGQ_).
1. If the filtered terminal voltage ($V_{\text{t,filt}}$) of the WTG falls below $V_{\text{wgo}}$, then the WGO function is initiated.

2. The power reference is then held at $P_{\text{wgo}}$ until the voltage recovers to above ($V_{\text{wgo}} + \epsilon$).

3. After this point the power reference is ramped at a rate of $rpw_1$ to the next level $P_{\text{wgo}}$ and is held there (at $P_{\text{wgo}}$) for $Thold$ seconds.

4. Then, finally, the power reference is ramped back to its initial value at a rate of $rpw_2$.

5. Presently, the intent is to implement this model to work as shown in Figure 10 with either the REPC_A or REPC_C models. It will not, for the initial implementation, be configured to function with the REPC_B (multiple device controller) model. Furthermore, at the discretion of the software vendors they may for now configure the initial implementation to work only with type 4, PV and BESS models, to be possibly extended in the future to function with type 3 WTGs models. In the case of type 3 WTG, the $Prf'$ output from WGO will need to be fed to both the $\text{wtgp}_a$ and $\text{wtgq}_*$ models.

Once initiated, the WGO follows through the whole process.

To illustrate its effectiveness, we developed a user-written model of this proposed auxiliary control in GE PSLF™ and used it on the existing RES generic models to illustrate its behavior for a simple test case. The results are shown in Figures 11 to 15. As can be seen the user-written model performs as expected. Figure 16 shows the actual performance of the type 4 WTG, with the WGO supplemental controls, as presented by Siemens Wind in March 2017 to the WECC MVWG [7]. As can be seen the performance of the model is very similar to the actual WTG performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{wgo}}$</td>
<td>Voltage threshold below with the WGO function is initiated [pu]</td>
<td>0.5 – 0.6</td>
</tr>
<tr>
<td>$P_{\text{wgo}}$</td>
<td>Power reference held during a fault when WGO is initiated [pu]</td>
<td>0.4 – 0.6</td>
</tr>
<tr>
<td>$rpw_1$</td>
<td>Ramp rate at which power is increased from $P_{\text{wgo}}$ to $P_{\text{wgo}}$ [pu/s]</td>
<td>0.2 – 2</td>
</tr>
<tr>
<td>$P_{\text{wgo}}$</td>
<td>Power reference held for $Thold$ seconds after the fault [pu]</td>
<td>0.5 – 0.7</td>
</tr>
<tr>
<td>$rpw_2$</td>
<td>Ramp rate at which power is increased from $P_{\text{wgo}}$ back to normal [pu/s]</td>
<td>0.2 – 2</td>
</tr>
<tr>
<td>$Thold$</td>
<td>Time for which the power reference is held at $P_{\text{wgo}}$ [s]</td>
<td>1 – 2</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Small hysteresis on voltage recovery to start the first ramp [pu]</td>
<td>0.01 – 0.02</td>
</tr>
</tbody>
</table>
Figure 11: Type 4 WTG generic model with the user-written WTGWGO_A model. Fault at WTG terminals resulting in 0% retained voltage.

Figure 12: Type 4 WTG generic model with the user-written WTGWGO_A model. Fault at WTG terminals resulting in ~30% retained voltage.
Figure 13: Type 4 WTG generic model with the user-written WTGWGO_A model. Fault at WTG terminals resulting in ~60% retained voltage.

Figure 14: Type 4 WTG generic model with the user-written WTGWGO_A model. Fault at WTG terminals resulting in ~75% retained voltage – WGO is not initiated since voltage does not go below the threshold ($V_{ago}$).
Figure 15: Type 4 WTG generic model with the user-written \texttt{WTGWGO-A} model. Fault at WTG terminals resulting in 0% retained voltage. The WGO has little impact, as would be expected, since the initial output of the WTG is below right at the hold threshold $P_{\text{wgo2}}$ of the WGO settings.

Figure 16: Actual performance of a WTG using the WGO for a Siemens WTG as presented to WECC MVWG [7].
Another auxiliary control feature that is available from many wind turbine manufacturers is the so-called inertial-based fast-frequency response (IBFFR) controls. It is outside of the scope of this document to describe this functionality and its many aspects and nuances. A proposal has been presented at a few previous WECC MVWG meetings [8]. Here, based on [8], a simple user-written model was developed in GE PSLF™ to demonstrate the proposed model for IBFFR. We call it the WTGIBFFR_A model. It is shown in Figure 17. The model, the underlying assumptions behind it, and its functionality may be explained as follows:

- Although it is understood that the actual implementation of the so-called inertial-based fast-frequency response is perhaps quite different among the various wind turbine generator manufacturers, nonetheless, for the purposes of a generic model one can define four (4) regions in the response, as shown in Figure 17, namely:
  - $T_{rise}$ – 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.
  - $T_{peak}$ – 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. $Peak = Po \times (1 + dP)$
  - $T_{fall}$ – 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. $P_{min} = Po \times (1 - dP_{min})$.
  - $T_{rec}$ – 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 18, and Figure 19 shows how it fits into the mix of the RES models. It was implemented, as a user-written model, and tested on a small test system. Some example simulations are shown in Figures 20, 21 and 22. 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 [14]. The function $F1$ represents the following simple logic: if $err \leq dbd$ 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 $s0 \geq dP \cdot Po$ then $out = 1$, else $out = 0$. Then $out2 = out$ (the output of $F2$) after a delay of $T_{peak}$ seconds. Where $Po$ here (and in all

---

12 The name IBFFR for this function/model is tentative, and the final naming convention will be discussed in future WECC meetings once this model starts to be implemented by the software vendors.
13 This is sometime referred to in the literature as "synthetic inertia" or "emulated inertia" but we prefer the terminology of inertia-based fast-frequency response.
14 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)
cases below) denotes the initial turbine electrical power output as determined from the initial power flow solution.

- The function $F_3$ represents the following simple logic: if $s_1 \leq -(dP + dP_{\text{min}})P_0$ then out3 = 1, else out3 = 0.

- The rise for recovery ($T_{\text{rec}}$) 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 (Area A in Figure 17) is equal to the energy returned to the shaft (Area B in Figure 17). It is can easily be shown that:

$$T_{\text{rec}} = \frac{2dP}{dP_{\text{min}}} \left[ \frac{\text{rise}}{2} + T_{\text{peak}} + \left( \frac{dP}{dP_{\text{max}} + dP_{\text{min}}} \right) \frac{T_{\text{fall}}}{2} \right] - T_{\text{fall}} \left( 1 - \frac{dP}{dP_{\text{max}} + dP_{\text{min}}} \right) \tag{1}$$

- Finally, a perusal of the table of parameters (Table 8) will show that we have assigned six (6) sets of values of $dP, dP_{\text{min}}, T_{\text{rise}}, T_{\text{peak}}$, and $T_{\text{fall}}$, associated with six different power levels of the turbine ($p_1$ to $p_6$). 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). Thus, this matrix of $6 \times 6$ values works in the following way:

```plaintext
if (P_0 \geq p_6)
  dP = dP_6
  dP_{\text{min}} = dP_{\text{min}6}
  T_{\text{rise}} = T_{\text{rise}6}
  T_{\text{peak}} = T_{\text{peak}6}
  T_{\text{fall}} = T_{\text{fall}6}
elseif (P_0 \geq p_5)
  dP = dP_5
  dP_{\text{min}} = dP_{\text{min}5}
  T_{\text{rise}} = T_{\text{rise}5}
  T_{\text{peak}} = T_{\text{peak}5}
  T_{\text{fall}} = T_{\text{fall}5}
elseif (P_0 \geq p_4)
  dP = dP_4
  dP_{\text{min}} = dP_{\text{min}4}
  T_{\text{rise}} = T_{\text{rise}4}
  T_{\text{peak}} = T_{\text{peak}4}
  T_{\text{fall}} = T_{\text{fall}4}
elseif (P_0 \geq p_3)
  dP = dP_3
  dP_{\text{min}} = dP_{\text{min}3}
  T_{\text{rise}} = T_{\text{rise}3}
  T_{\text{peak}} = T_{\text{peak}3}
  T_{\text{fall}} = T_{\text{fall}3}
elseif (P_0 \geq p_2)
```

15 The energy taken back from the system to speed up the turbine (Area B in Figure 17), in a real system, is likely slightly greater than the energy injected into the grid (Area A in Figure 17) at the onset of IBFFR. Thus, the two are not necessarily equal, 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 the generic stability level model presented here, such losses are not modeled and so 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.
\[ \frac{dP}{dt} = \frac{dP_2}{dt} \]
\[ dP_{min} = dP_{min2} \]
\[ T_{rise} = T_{rise2} \]
\[ T_{peak} = T_{peak2} \]
\[ T_{fall} = T_{fall2} \]
\[ \text{elseif} \ (P_o \geq p_1) \]
\[ \frac{dP}{dt} = \frac{dP_1}{dt} \]
\[ dP_{min} = dP_{min1} \]
\[ T_{rise} = T_{rise1} \]
\[ T_{peak} = T_{peak1} \]
\[ T_{fall} = T_{fall1} \]
\[ \text{else} \]
\[ \text{Model is inactive – that is there is no IBFR} \]
\[ \text{end} \]

Now it should be noted that the actual IBFFR that is supplied by each individual turbine in a wind power plant is dependent on many factors, and most importantly on (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 those 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, IBFFR 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.

With all of the above in mind, Figures 18 to 22 show example simulations with the model and we see a reasonable performance, and the fact that the IBFFR changes with the initial WTG power level as expected. Also, we see that the speed transients in the WTG are reasonable – i.e. speed initial declines as energy is extracted from the shaft and then speeds up again once energy is slowly put back into the shaft after the IBFFR is completed and we are in the recovery phase of IBFFR. Note: the IBFFR model should be used only in frequency stability studies. This simple model will not behave well if used when performing simulations of transmission faults close to the terminals of the WTGs, thus it is not for studying a combination of faults and frequency events.
Figure 17: Characteristic of the IBFFR (from [8]).

\[
P_{\text{max}} = (1 + dP)P_0
\]

\[
P_{\text{min}} = (1 - dP_{\text{min}})P_0
\]

\[
\text{Area A}
\]

\[
\text{Area B}
\]

Figure 18: Block-diagram of the implemented WTGBFFR_A model.
Figure 19: 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 8: Parameter List for WTGIBFFR_A model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical Range/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dbd</td>
<td>Deadband below which IBFFR is initiated, that is when $(1 - \text{frequency}) \geq \text{dbd}$, then the IBFFR is initiated [pu]</td>
<td>0.0008 – 0.0017</td>
</tr>
<tr>
<td>[p1, p2, p3, p4, p5, p6]</td>
<td>Six (6) power points corresponding to the six sets of parameters [pu]</td>
<td>N/A</td>
</tr>
<tr>
<td>[dP1 to dP6]</td>
<td>Six $dP$ values (see Figure 17) [pu]</td>
<td>0.05 – 0.1</td>
</tr>
<tr>
<td>[dPmin1 to dPmin6]</td>
<td>Six $dP_{\text{min}}$ values (see Figure 17) [pu]</td>
<td>0 – 0.08</td>
</tr>
<tr>
<td>[Tt1 to Tt6]</td>
<td>Six $T_{t}$ values (see Figure 17) [s]</td>
<td>0.1 – 0.2</td>
</tr>
<tr>
<td>[Tpeak1 to Tpeak6]</td>
<td>Six $T_{\text{peak}}$ values (see Figure 17) [s]</td>
<td>1 – 2</td>
</tr>
<tr>
<td>[Tfall1 to Tfall6]</td>
<td>Six $T_{\text{fall}}$ values (see Figure 17) [s]</td>
<td>0.2 – 0.5</td>
</tr>
<tr>
<td>[Trec1 to Trec6]</td>
<td>Six $T_{\text{rec}}$ values (see Figure 17) [s]</td>
<td>0</td>
</tr>
</tbody>
</table>

**Very Important Note:**
The six (6) $T_{\text{rec}}$ values in the model should typically be set to zero (0). By doing so the model internally calculates the value of $T_{\text{rec}}$ for each operating point using equation (1) in the above section. If, however, the user wishes to define a $T_{\text{rec}}$ that is greater than the calculated value using equation (1), for each of the designated six operation points, then the user may populate the $T_{\text{rec}}$ parameters. This may be done in cases where the user may wish to represent the fact that Area B is actually larger than Area A in some cases due to losses during the period of power injection as the turbine speed significant 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 $T_{\text{rec}}$ that is less than the value calculated by equation (1), then the model will ignore the user defined value and use that calculated by equation (1). 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.
Figure 20: Simulation of the performance of the WTGIBFFR_A on a test case for a type 4 WPP using the generic RES models. Plant is initially at a high output.
Figure 21: Simulation of the performance of the WTGIBFFR\textsubscript{A} on a test case for a type 4 WPP using the generic RES models. Plant is initially at a lower output than the previous case. We can see the difference in the IBFFR response for the same event.

![Figure 21](image)

Figure 22: Same cases as Figure 19 – illustrating the fact that the energy for the IBFFR response is being taken out of the rotor-shaft and then put back in – i.e. shaft speed goes down initially and then slowly speeds back up to its initial value.

![Figure 22](image)
Acknowledgements:

PEACE® wishes to gratefully acknowledge EPRI research funding for time spent by PEACE® staff to prepare this memo and develop and test the user-written models presented in section 6.0. Furthermore, EPRI’s funding and development of the user-written versions of REGC_B and REGC_C in [4] are gratefully acknowledged. Moreover, the continued efforts and contributions of GE, Siemens PTI, PowerWorld and PowerTech Labs are gratefully acknowledged. In addition, we acknowledge the input, comments and participation of many of the equipment vendors in this effort, including FirstSolar, Senvion and Siemens-Gamesa, as well as GE and Vestas who have been present at various meetings where the work here has been discussed.

Needless-to-say, a debt of gratitude is due to the WECC Modeling and Validation Working Group (S. Wang chairperson) and Renewable Energy Modeling Task Force (S. Zhu chairperson) for hosting the open forum for these discussions and developments. There are numerous members of the WECC MVWG and REMTF who have provided comments, input and suggestions during the course of these efforts, and it would be difficult at best to attempt to properly capture all names.

Finally, needless-to-say, all entities involved in this activity self-fund within their own organizations their travel expenses to come to the WECC MVWG meetings where much of this is discussed. This is gratefully acknowledged.

We apologize for any inadvertent omissions.

References: