Model User Guide for Generic Renewable Energy System Models

3002027129

Model User Guide for Generic Renewable Energy System Models

3002027129

Technical Update, October, 2023

EPRI Project Manager

D. Ramasubramanian

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪650.855.2121▪ askepri@epri.com ▪ www.epri.com

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Power and Energy, Analysis, Consulting and Education, PLLC

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

ACKNOWLEDGMENTS

The following organization, under contract to the EPRI, prepared this report:

Power and Energy, Analysis, Consulting and Education, PLLC
457 Laurence Dr #139
Heath, TX 75032

Principal Investigator
P. Pourbeik

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Model User Guide for Generic Renewable Energy System Models: EPRI, Palo Alto, CA: 2023. 3002027129.

ABSTRACT

Through broad industrywide efforts since 2010, EPRI has played a key lead technical role in the development of a new set of generic and public models for renewable energy systems (RESs). To date, the majority of the work has been done through engagement with the Western Electricity Coordinating Council's (WECC) Modeling and Validation Subcommittee and its Renewable Energy Modeling Working Group. Two previous versions of this report were released in 2015 and 2018, which described in detail these generic models and their usage. Since 2018, a range of new models have been added to the library of generic RES models. Thus, this third revision of the RES model user guide replaces the earlier versions by providing the following:

- An overview of the types of inverter based resources (IBRs), the majority of which are RES that can be modeled with the second-generation generic RES models
- A summary of the second-generation RES generic models and additional work being done to enhance them
- A detailed account of each of the modules used in the second-generation generic RES models

Keywords
IBR modeling
Wind turbine generators
Photovoltaic generation
Energy storage
Renewable energy system models

CONTENTS

ABSTRACT .... **v**

1 **INTRODUCTION** **1-1**

2 **BRIEF SUMMARY OF INVERTER BASED RESOURCE TECHNOLOGIES** **2-1**

3 **THE SECOND GENERATION GENERIC RENEWABLE ENERGY MODELS** **3-1**

3.1 The Model Library 3-1

3.2 Modeling IBR Power Plants 3-3

3.3 Grid-Forming versus Grid-Following Inverters 3-5

3.4 Additional Models Under Development 3-5

4 **THE 2ND GENERATION GENERIC RES MODELS** **4-1**

4.1 Renewable Energy Generator/Converter Models 4-2

4.2 Renewable Energy Electrical Controls Models 4-9

4.3 Renewable Energy Plant Controls Models 4-23

4.4 Wind Turbine Generator Mechanical Side Models and Other Auxiliary Models 4-37

4.5 Putting the Models Together to Develop IBR Plant Models 4-51

5 **SUMMARY AND RECOMENDATIONS** **5-1**

6 **REFERENCES** **6-1**

A **CURRENT LIMIT LOGIC FOR REEC_A** **A-1**

B **CURRENT LIMIT LOGIC FOR REEC_D** **B-1**

LIST OF FIGURES

Figure 2-1 The four main wind turbine technologies. 2-2
Figure 3-1 Simple aggregated model for an IBR power plant 3-4
Figure 3-2 Complex plant aggregate model. 3-4
Figure 4-1 REGC_A Model 4-5
Figure 4-2 REGC_B Model 4-5
Figure 4-3 REGC_C Model 4-6
Figure 4-4 Example simulation of REGC_* models for a remote fault. 4-6
Figure 4-5 Example simulation of REGC_* models for a remote fault, for a weakened system condition. 4-7
Figure 4-6 REEC_A Model 4-10
Figure 4-7 REEC_C Model 4-10
Figure 4-8 REEC_D Model 4-11
Figure 4-9 Options for the reactive power control path in the REEC_A model. 4-13
Figure 4-10 State transition diagram for the REEC_A model reactive current injection during a voltage-dip. 4-14
Figure 4-11 Current limit for REEC_A model. 4-15
Figure 4-12 Extra part of the *reec_c* model for simulating charging and discharging of a storage mechanism. 4-16
Figure 4-13 The REPC_A power plant controller model 4-24
Figure 4-14 The REPC_C power plant controller model. The key difference with REPC_A are shown highlighted in RED 4-25
Figure 4-15 The proposed REPC_D hybrid-PPC model. 4-26
Figure 4-16 The two (2) control paths of the power plant controller model. 4-29
Figure 4-17 Switching logic for the automated switching of MSSs 4-30
Figure 4-18 The active power control path for REPC_A and REPC_C. The differences are shown in RED. 4-34
Figure 4-19 The WTGA_A aero-dynamic model based on [21]. 4-37
Figure 4-20 The WTGT_A model – to be used with type 3 WTGs only. 4-38
Figure 4-21 The WTGT_B model – to be used with type 4 WTGs only. 4-39
Figure 4-22 The simulation of a nearby fault, for a type 4 WTG using the WTGT_A model (without *Tp*) and the WTGT_B model (with *Tp*). 4-39
Figure 4-23 The WTGP_A model 4-41
Figure 4-24 The WTGP_B model 4-41
Figure 4-25 The WTGQ_A model 4-43
Figure 4-26 The WTGWGO_A model 4-44
Figure 4-27 Characteristic of the IBFFR model [9] 4-48
Figure 4-28 The WTGIBFFR_A model 4-49

LIST OF TABLES

Table 3-1 Model names as they appear in various commercial tools based on the latest versions of the tools as of the date of publication of this document. These models are available in some other commercial software platforms also, such as DigSilent PowerFactory, EMTP, etc. Thus, this table is not comprehensive but only covers the most commonly used tools for positive-sequence simulations in North America. 3-3

Table 4-1 Summary of 2nd generation RES models 4-2

Table 4-2 Parameter list for the REGC_* models 4-8

Table 4-3 Reactive power control modes for the REEC_A model........ 4-13

Table 4-4 Parameter list for the REEC_* models........ 4-20

Table 4-5 Parameters for the REPC_* models 4-35

Table 4-6 Parameter list for the WTGT_* models. 4-40

Table 4-7 Parameter list for the WTGP_* models........ 4-42

Table 4-8 Parameter list for the WTGQ_A model 4-43

Table 4-9 Parameter list for WTGWGO_A model 4-44

Table 4-10 Parameter list for the WTGIBFFR_A model 4-50

Table 4-11 Models that can be used for modeling each type of IBR plant. Note, only ONE model should be chosen in each category. 4-52

1 INTRODUCTION

In 2014, at the culmination of extensive research and development, the Electric Power Research Institute (EPRI), working together with many stakeholders within the industry, helped to develop the second generation of generic stability models for wind generators and photovoltaic generation. These models were developed in a modular format to facilitate the ability to add new modules to the library of these models, as new features and functions for power electronic based generations develops through the years. From the initial release of these so-called 2nd generation generic renewable energy system (RES) models two rounds of new models have been developed, in 2016/17 time frame a generic battery energy storage model, and a complex plant controller were developed as modules that were added to the library of models. While more recently starting in 2018 and culminating in 2022, a series of new modules were developed to enhance various elements including new generator/converter models, a new electrical controls model, a new power plant controller model, and several additional auxiliary controllers. Although EPRI has lead much of the technical development and testing of the models, the effort has been a broad industry effort with true collaboration among many stakeholders including several commercial power system simulation software vendors, equipment manufacturers, utilities, national laboratories and many others. The collaborative community of stakeholders has worked under the Western Electricity Coordinating Council's (WECC) Modeling and Validation Subcommittee (MVS). These models are presently all available in several of the major commercial software platforms, namely, Siemens PTI PSS®E, GE PSLFTM, PowerWorld Simulator, PowerTech Labs TSATTM and DigSilent PowerFactory. In all cases the software vendors adopted the model by their own choice and much internal effort. More recently these generic model structures have been adopted by some software vendors of electromagnetic transient (EMT) simulation platforms, such as EMTP®.

The detailed model specifications may be found in [1], which is the WECC approved document and definitive model specification. References [2], [3], [4], [5], [6], [7], [8] and [9] provide other details and the documentation of the gradual development of the models, as well as testing and validation results. We will not repeat any significant portion of these materials in this report, as all these documents are publicly available.

It should be noted that the International Electrotechnical Commission (IEC) Technical Committee (TC) 88, Working Group (WG) 27 also completed its work in 2020[1], developing specifications for an international standard on generic models for wind turbine generators. This, however, only covers wind turbine generators. EPRI has also been engaged in this work, particularly in the early stages of the work (2010 – 2013). The IEC models are for the most part quite similar to the 2nd generation generic RES models developed here in the US, but they do

[1] IEC 61400-27-1:2020-07(en), Wind energy generation systems – Part 27-1: Electrical simulation models – Generic models. https://standards.iteh.ai/catalog/standards/iec/3723afad-4d5c-4b97-afa4-e7d9c18ad043/iec-61400-27-1-2020

have some differences, particularly with respect to the type 3 wind turbine generators (see [4], [5] and [10]). It is outside the scope of this document to further discuss these issues.

Thus, in summary this document is a revision of the earlier versions of this report such that it covers all the previous materials and includes now a description of the latest models developed that have been added to the library of the so-called 2nd generation generic RES models developed in the US, primarily within the WECC MVS.

The remainder of this document is organized as follows:

Section 2 – gives a very brief overview of the types of inverter based resources (IBR), the majority of which are RES, which can be modeled with the 2nd generation generic RES models.

Section 3 – gives a summary of the so-called 2nd generation RES generic models and where additional work is being done to enhance them.

Section 4 – provides a detailed account of each of the modules that are used in the 2nd generation generic RES models.

Section 5 – provides a brief conclusion to the report.

Section 6 – is a list of the references used in this report.

Appendices – provide various supporting information.

2

BRIEF SUMMARY OF INVERTER BASED RESOURCE TECHNOLOGIES

When the 2nd generation generic renewable energy system (RES) models were first developed, it was decided to make them modular. Also, the naming convention was chosen at the time to the modules:

- the Renewable Energy Generator/Converter (REGC_*) models,
- the Renewable Energy Electrical Controls (REEC_*) models,
- the Renewable Energy Plant Controller (REPC_*) models,
- and then a number of other primarily mechanical system models for wind turbine generators.

Thus, they are referred to as the 2nd generation generic RES models. All such RES are interfaced with the grid through power electronic converters. Moreover, since they are primarily generation devices, the converter is primarily functioning in the role of a power inverter. That is, converting the dc current (power) on the resource side to ac current (power) on the grid side. Thus, recently the more common industry term used to refer to such resources is Inverter Based Resources (IBR). In the context of this report the terms RES and IBR are used interchangeably since they essentially refer to the same technology. Battery Energy Storage Systems (BESS) are also clearly an IBR, although obviously the power converter interface acts in a power rectifier mode when charging from the ac grid[2], none-the-less for the sake of simplicity BESS is often referred to as both IBR and RES.

The four (4) main configurations of wind turbine generator (WTG) technologies are shown in Figure 2-1. The so-called type 1 and 2 WTGs, which utilized simple passive induction generators, are also renewable energy resources. The previous edition of this report [11] discusses how these types of older WTG technologies can be modeled using the generic models. This subject is not covered here in this present report, since these older technologies of WTGs are no longer manufactured by the major WTG equipment manufacturers, and have not been in production for well over a decade or more. There are still some significant installations of these older technologies around the world, but most are reaching their end of life and being replaced by the latest IBR type WTGs. Thus, this subject is not covered here. The interested reader can refer to documents such as [11] and [12] for a discussion on type 1 and 2 WTGs.

[2] In some installations of BESS, with for example photovoltaic systems, the BESS can be connected on the dc side of the inverter, and charging may only be done on the dc side when there is excess energy resource.

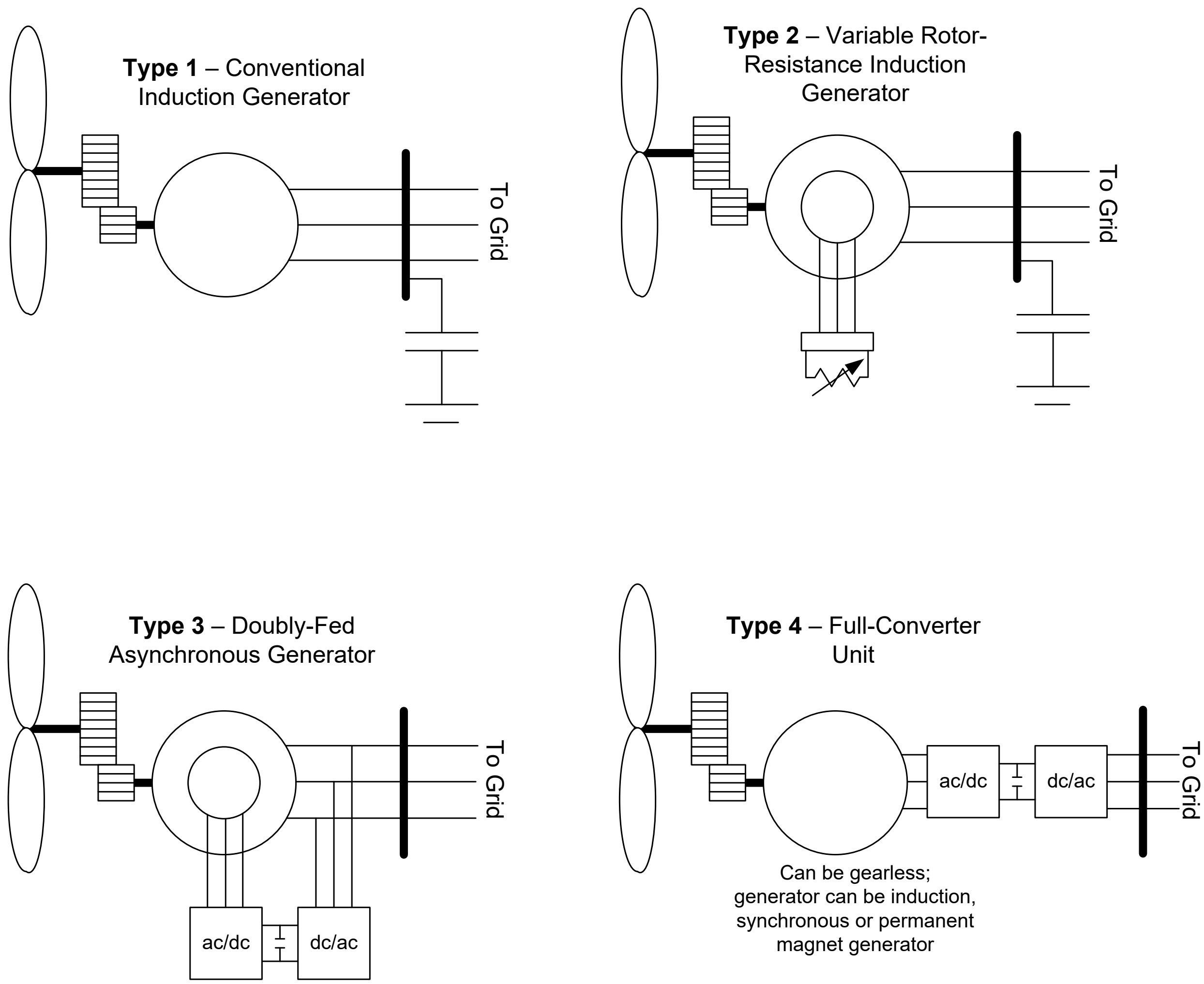


Figure 2-1
The four main wind turbine technologies.

Thus in summary, the key RES technologies that can be modeled with the 2nd generation RES models are:

Type 3 WTGs power plants

Type 4 WTGs power plants

Photovoltaic (PV) power plants

Battery Energy Storage Systems (BESS)

There is also the ability to model hybrid-plants, however, this aspect is current under revision with a new proposed hybrid-plant controller under development to enhance this feature. The new proposed hybrid-plant controller is not discussed in this document.

3
THE SECOND GENERATION GENERIC RENEWABLE ENERGY MODELS

3.1 The Model Library

The complete 2nd generation generic RES models, with the latest additions since 2018, now includes a total seventeen (17) generic individual models:

REGC_A
REGC_B
REGC_C
REEC_A[3]
REEC_C
REEC_D
REPC_A
REPC_B
REPC_C
WTGT_A
WTGT_B
WTGAR_A
WTGPT_A
WTGPT_B
WTGTRQ_A
WTGWGO_A
WTGIBFFR_A

In addition to the above, there is one extra model (WT1P_B) that was developed to enhance the modeling of the pitch-controller for type 1 and 2 WTGs. As discussed in the previous section, this document focuses on inverter based resources (IBR) and so the reader interested in this new pitch-controller model should refer to [1].

In addition to the above models the following standard protection models exist in many software tools that can be used for modeling the low/high voltage and frequency ride-through capabilities of the IBR units:

LHVRT
LHFRT

The above protection models have existed in the commercial simulation software since before the development of the 2nd generation RES models. Thus, these models are not further discussed here and their use is clearly described in the respective user's manual of the software tools. They

[3] The so-called REEC_B model was essentially abandoned in North America a few years ago, when it was removed from the approved model lists in WECC and the Eastern Interconnection due to the lack of proper representation of the voltage dependent current-limits of the inverter.

can be used to emulate the low/high voltage and frequency ride-through capabilities of the IBR units by using a set of ten (10) pairs of points which define delta voltage (frequency) points and the corresponding trip times. For example, if the first pair of points is set to *dvtrp1* = – 0.9 and *dttrp1* = 0.1, this means that if the voltage at the monitored bus (typically, set to the terminals of the IBR unit) falls by more than 0.9 pu from the nominal voltage (*vref*, typically set to 1.0 pu) for more than 0.1 seconds, then the unit will trip. The points must be entered sequentially. The user's manual of the specific commercial software tool used should be carefully reviewed for these protection models to clearly understand the requirements of each software tool for using the model[4].

An important note to be observed with regards to the usage of the frequency trip relays in positive-sequence simulation platforms is that due to the way that frequency is calculated in such simulation platforms, there is always the possibility of false frequency trips when a fault is placed nearby the monitored bus of the frequency relay. Rather than repeating the details, this is explained carefully in a WECC white paper[5]. With this in mind, it is perhaps prudent to place frequency relays on alarm only, rather than allowing them to trip the unit, so that the user can peruse the results of the simulation to see if the alarmed tripped were false trips or potentially legitimate trips. For example, it the relay attempts to trip the unit for an over-frequency of 61 Hz (on a 60 Hz system) when a fault is placed nearby the plant, this is clearly a false trip due to issues related to calculated frequency.

In summary, the above library of models can be used to model wind power plants, PV power plants and BESS. In the next section this will be discussed in detail.

Note that the names for the models presented here, and used throughout the report, are consistent with the names presented in the original model specifications that were developed through wide industry collaboration [1], [13]. In the various commercial software tools, where these models are available, the names of the model vary a little from those mentioned here. Table 3-1 below summarizes the cross-referencing of the model names across the major tools used in North America.

---

[4] **Note:** in some of the software tools each instantiation of a delta voltage (frequency) and trip time pair is a separate model, and thus any number of point may be defined. Again, the specific user's manual of each software tool should be carefully reviewed to understand the exact usage of the voltage and frequency relay models.

[5] https://www.wecc.org/Reliability/WECC_White_Paper_Frequency_062618_Clean_Final.pdf

Table 3-1
Model names as they appear in various commercial tools based on the latest versions of the tools as of the date of publication of this document. These models are available in some other commercial software platforms also, such as DigSilent PowerFactory, EMTP, etc. Thus, this table is not comprehensive but only covers the most commonly used tools for positive-sequence simulations in North America.

Model Name per Specs	Model Name in Software Tools			
	GE PSLF™	Siemens PTI PSS®E	PowerWorld Simulator	PowerTech Labs TSAT™
REGC_A	regc_a	REGCAU2	REGC_A	REGC_A
REGC_B	regc_b	REGCBU1	REGC_B	REGC_B
REGC_C	regc_c	REGCCU	REGC_C	supported*
REEC_A	reec_a	REECA1	REEC_A	REEC_A
REEC_C	reec_c	REECC1	REEC_C	supported*
REEC_D	reec_d	REECDU1	REEC_D	REEC_D
REPC_A	repc_a	REPCTA1 & REPCA1	REPC_A	REPC_A
REPC_B	repc_b	PLNTBU1	REPC_B	supported*
REPC_C	repc_c	REPCCU	REPC_C	REPC_C
WTGT_A	wtgt_a	WTDTA1	WTGT_A	WTGT_A
WTGT_B	wtgt_b	WTDTBU1	WTGT_B	being developed
WTGA_A	wtga_a	WTARA1	WTGA_A	WTGA_A
WTGP_A	wtgp_a	WTPTA1	WTGP_A	WTGP_A
WTGP_B	wtgp_b	WTPTBU1	WTGP_B	being developed
WTGQ_A	wtgq_a	WTTQA1	WTGTRQ_A	WTGQ_A
WTGWGO_A	wtgwgo_a	WTGWGOAU	WTGWGO_A	WTGWGO_A **
WTGIBFFR_A	wtgibffr_a	WTGIBFFRAU	WTGIBFFR_A	WTGIBFFR_A**^
Protection Relay Models				
LHVRT	lhvrt	VTGTPAT (trips unit), VTGDCAT (disconnects bus)	LHVRT	supported*
LHFRT	lhfrt	FRQTPAT (trips unit), FRQDCAT (disconnects bus)	LHFRT	supported*
*supports PSS®E and PSLF formats ** works for REEC_A model for now *** requires additional files from Powertech Labs				

Note: In Siemens PTI PSS®E there are two versions of the REGC_A model. REGCA1 and REGCAU2. These are identical except for the fact that REGCAU2 includes the extra parameter Xe (generator effective impedance), which is used in some cases for type 3 WTGs. When Xe = 0 (which is the majority of cases, and certainly true for type 4 WTG, PV and BESS) either model can be used. In all the other software tools, Xe has always been part of the REGC_A model.

3.2 Modeling IBR Power Plants

For bulk power system stability analysis, where the main concern is the dynamic behavior of the power plant at the point of common coupling (PCC), based on industry experience, a simple model structure such as shown in Figure 3-1 may be used [10], [11]. This is the simplest case, where the IBR plant consists of a single type of IBR unit technology with a single substation power transformer connecting the collector system to the bulk electric system (BES). There are of course more complex scenarios, that will require modeling of multiple aggregated IBR units. One such example is shown in Figure 3-2.

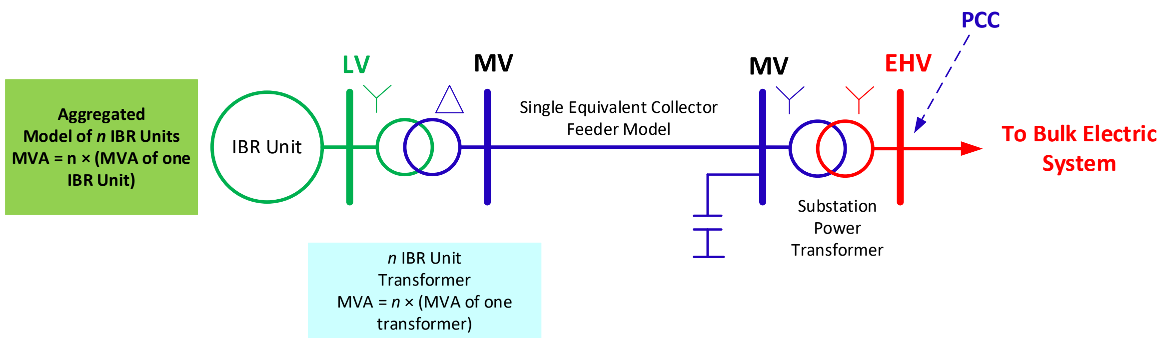


Figure 3-1
Simple aggregated model for an IBR power plant.

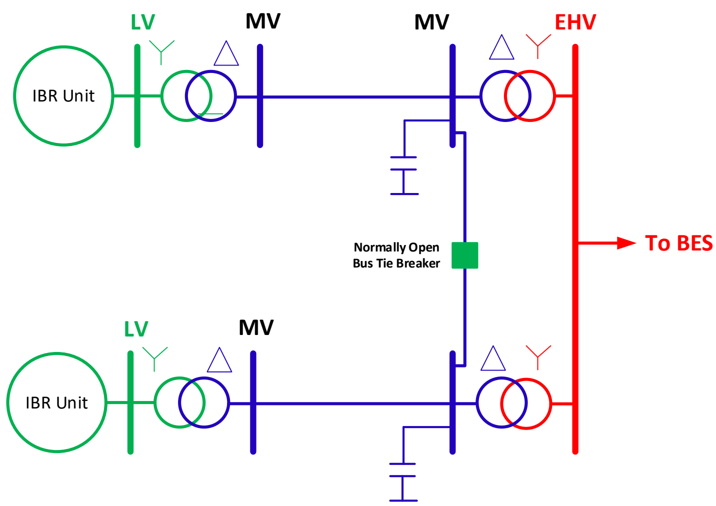


Figure 3-2
Complex plant aggregate model.

In all these examples, the components are modeled in power flow as follows:

1. The substation transformer is modeled explicitly using the transformer nameplate data. When modeling an existing IBR power plant, it is imperative to properly model the taps, and fixed-tap settings, as set in the field at the plant.
2. The equivalent single feeder collector model is calculated from the detailed collector system data using the National Renewable Energy Laboratory (NREL) methodology to reduce it to a single equivalent feeder model [14] If the plant is a planned future plant with no present collector system data, a reasonable assumption might be $R = 0.011$ pu, $X = 0.027$ pu and $B = 0.069$ pu on 100 MVA base (this is an average value taken from the typical parameters in [15]).
3. The IBR unit step-up transformer is modeled based on the name plate data of a representative unit transformer, and the models MVA rating is simply scaled up by the number of turbines. For example, if a representative single IBR unit transformer has a leakage reactance of 0.06 pu on 1.5 MVA, and there are 100 units in the plant, then the aggregated IBR unit transformer is modeled as $Xt = 0.06$ pu on 150 MVA. These relatively small transformers typically have an X/R = 10.

4. The single aggregated IBR unit is modeled with the appropriate parameters for the specific equipment and the models MVA rating is again scaled up by the number of turbines in service. For example, if a single IBR unit is rated at 1.5 MVA and there are 100 units in the plant, then the aggregated unit is modeled with the same parameters as the single unit on 150 MVA.

With the above basics discussed, in the next section we discuss the details of how the IBR unit aggregated dynamic model is developed in positive-sequence simulation platforms using the 2nd generation generic models.

3.3 Grid-Forming versus Grid-Following Inverters

The models of IBR that are covered in this document are based primarily on fast inner-loop current control. To date there has been no distinction among these present models with respect to whether they fall into the category of so-called grid-following inverters (GFL), which are deemed to not be able to operate in an islanded system without any synchronous generation, versus so called grid forming inverters (GFM), which can operate even in an islanded system without any synchronous generation. Presently, many equipment vendors are starting to offer so-called GFM technologies, particularly for battery energy storage systems. GFM are also starting to be offered for photovoltaics and type 4 wind turbine generators. The details of GFL versus GFM technologies is outside of the scope of this document. EPRI, and others, are actively engaged in the development of standard generic models for so-called GFM inverters. That being said, the name of a generic model by itself should not be considered as being representative of GFL or GFM. In fact, when using a select configuration of the models covered in this document, it is indeed possible to simulate and run a 100% IBR network [16]. The interested reader may refer to documents such as the recent EPRI tutorial on GFM: https://www.epri.com/research/products/000000003002028090.

Finally, note that the misconception that only GFM technologies are capable of providing services such as primary frequency response, fast frequency response and voltage control should not be made. These high-level ancillary services can be provided by any technology, and can also be represented by the models covered in this document, the key in the end is ensuring overall system stability in each case.

3.4 Additional Models Under Development

In addition to the models discussed here, a few other models are presently under development. One is yet another enhancement of the electrical controls model (REEC_E), and the second is a more detailed hybrid-plant controller (REPC_D), which aims to eliminate some of the limitations of the current hybrid-plant controller model (REPC_B)[6]. A brief discussion of the limitations of the present hybrid-plant controller model (REPC_B) and the enhancements in the new hybrid-plant controller model (REPC_D) is given for completeness at the end of section 4.0.

[6] https://www.wecc.org/Reliability/Clarification%20on%20Proper%20Use%20of%20REPC%20models.pdf

4

THE 2ND GENERATION GENERIC RES MODELS

As indicated in the brief summary in the previous section, there are presently seventeen (17) modules (individual component models) that are available in the library of the 2nd generation RES models. These fall into five (5) broad categories:

- the Renewable Energy Generator/Converter (REGC_*) models which emulate the electrical generator/converter interface between the IBR unit and the electrical grid,
- the Renewable Energy Electrical Controls (REEC_*) models which emulate the automatic controls at the individual IBR unit level of the generator/converter,
- the Renewable Energy Plant Controller (REPC_*) models which emulate the overall centralized plant level automatic controller that sends control signals down to all the individual IBR units in a plant,
- the mechanical and aerodynamic models (WTG***_*) models which emulate the various mechanical components and associated automatic controls in wind turbine generators (WTG) such as the pitch-controller (WTGP_*), the torque controller (WTGQ_*), the aerodynamics (WTGA_*) and the drive-drain dynamics (WTGT_*), and
- the various auxiliary controllers such as the weak grid option controllers for type 4 WTG (WTGWGO_A) and the inertia-based fast frequency response model for WTGs (WTGIBFFR_A).

Table 4-1 summarizes the above statements.

In the next few subsections each of these categories of models are described in detail. It should be noted that the descriptions provided herein are an attempt of bringing about more in-depth understanding of the model structures and their usage. There are clearly software dependent syntax and usage instructions, which cannot be provided here and must be gleaned from the user's manual of each specific commercial software tool.

Table 4-1
Summary of 2nd generation RES models

Generator/Converter Models	Electrical Controller Models[7]	Power Plant Controller Models	WTG Mechanical and Aerodynamic Models	Auxiliary Controller Models
REGC_A REGC_B REGC_C	REEC_A REEC_C REEC_D	REPC_A REPC_C	WTGA_A WTGQ_A WTGP_A WTGP_B WTGT_A WTGT_B	WTGWGO_A WTGIBFFR_A

4.1 Renewable Energy Generator/Converter Models

There are presently three (3) Renewable Energy Generator/Converter (REGC) models:

- REGC_A – this model was originally developed and first released around 2014 in commercial tools [1]. It is a current-source interface model. The model is intended to model a voltage-source converter (VSC) based IBR resource. Since conventional inverter have inner-current control-loops that tightly control current and keep the current injected by the inverter tightly regulated, it was assumed that the inner-current control-loops and the phase-locked loop (PLL) can be neglected (as their dynamics is of a higher bandwidth) and the current injection can be modeled as a current source in software. These assumptions are valid, as will be illustrated below, so long as the strength of the system at the node where the device is connected is quite strong (e.g., generally a short circuit ratio of greater than 3 to 5, but can be dependent on the system location).
- REGC_B – this model was developed in 2018 [9] and first released around 2019/2020 in commercial tools. It is a voltage-source interface model based on research done at ASU [17]. The model still neglects the dynamics of the inner-current control-loops and the PLL. However, by introducing a voltage source behind an impedance in the network interface and thus making the *d* and *q* axis voltage components of the source into states of the model, it achieves greater numerical stability for modeling IBR in weaker network conditions.
- REGC_C – this model was developed by EPRI in 2019/2020 [18] and incorporated into many commercial tools (both positive-sequence and EMT) in 2022. It is also a voltage-source interface model, but additionally includes a generic representation of the inner-current control-loops and the PLL. Thus, it attempts to stretch the application of positive-sequence phasor-domain simulations a little further for weak-grid connection points. Clearly, EMT models will always include inner current control loop and PLL, if it exists in the equipment that is being modeled.

The three (3) models are shown respectively in Figure 4-1, Figure 4-2 and Figure 4-3. The parameter list for the models is provided in Table 4-2.

---

[7] A model called REEC_B had been developed years ago, but it is no longer recommended for use since it was too simplified and did not capture the voltage-dependent current limitations of the inverters. There is also presently an REPC_B plant controller model that is presently in use. However, it has some limitations and soon to be replaced by a new model REPC_D.

The following key observation are pertinent:

1. The range of each parameter value, and the suggested typical value of each parameter, as presented in Table 4-2 is simply for the purposes of providing some initial guidance. They are not to be taken as absolute limits on the possible values of the parameters. There may be perfectly legitimate values for the parameters, when the model is properly parameterized for a specific purpose, that are outside of the suggested range of values. Care must always be taken to properly, and meaningfully, parameterize the models, and if modeling an actual project to consult the OEM.
2. In general, all of these three models relate more closely to full-converter connected devices such as type 4 wind turbine generators, photovoltaic generators and battery energy storage systems. This is because there is no explicit modeling at all of the stator flux-dynamics, or any other representation, of the direct connected stator windings of a type 3 wind turbine generator (WTG) in these models. Nevertheless, all three models have, and continue to be, used for representing type 3 WTGs in bulk-grid analysis of renewables in positive-sequence phasor-domain tools. It has been shown that for the purposes of such simulation work the models can be validated against type 3 WTGs [4], [13].
3. Parameter numbers 1 to 8 (see Table 4-2) pertain to REGC_A only, and are associated with the current-source approach to modeling the network interface. Parameters 4 to 8, moreover, are not physically based parameters of the actual device but rather parameters used in the algebraic network solution algorithm at the interface of the current-source to the network equations to help with the numerical solution.
4. Parameters 12 and 13 (iqrmax/iqrmin) are used rarely. These rate limits on reactive current were used by only one of the original equipment manufacturers (OEMs) that were studied in [5]. Furthermore, in that one case they were invoked when the turbine is operating in local constant Q control for that vendor. That is, the turbine is holding a constant reactive power output. In this case these limits are imposed post fault, such that Iqrmax is active if the initial reactive output of the unit was above zero, and Iqrmin is active if the initial reactive output is negative. The purpose of the rate limits is to limit rate of recovery of the reactive power to its initial value after fault clearing. The user is cautioned not to use this feature unless instructed by the OEM or if they are certain of what they wish to accomplish. Thus, in almost all cases these limits are not used, nor implemented, in equipment and thus should be set to large values such as 999/-999 to essentially disable the limits.
5. Parameters 15 and 15 (xe and re) represent the source impedance of the VSC converters. Almost always, the resistance component is neglected (re = 0). Important Note: for REGC_A the value of xe is typically set to 0; it is, however, used in some cases for type 3 wind turbine generators to emulate the effective reactance of the generator and thus emulate the initial fault current of the generator. In these cases the value of xe used by the vendor may be quite large (e.g. 0.8 pu) and this is reasonable. For REGC_B and REGC_C the value of xe is intended to emulate the effective source impedance of the VSC full-converter and is more typically in the range of 0.1 to 0.2 pu and generally represents the smoothing reactor/filter of the VSC.
6. Parameters 20 to 25 (inner-current control loop gains and PLL gains and limit) pertain to the simple representation of the inner-current control loops and the phase-locked loop (PLL). These gains are tunable and so there is no effective limited range of values, and instead depend on the grid conditions into which the inverter is being deployed. The value of these

parameters should come from the OEM, or derived from benchmarking with a higher order model.

From a model application perspective, consider Figure 4-4. In this figure an IBR plant is modeled using the generic models in this report. The generator/converter, however, is modeled three (3) different ways. First, using REGC_A, then with REGC_B and finally with REGC_C. The system is a small, but realistic system with both IBR and conventional power plants. A remote fault and tripping of a transmission line is simulated. As can be seen the results from all three models match almost perfectly. Moreover, to the extent possible the exact same system was modeled in an EMT software tool using the EPRI developed generic IBR EMT models[8]. As can be seen for the relatively strong system conditions (i.e., short circuit ratio of > 5) the positive-sequence simulation results also match well with the EMT simulation results. Now consider Figure 4-5. In this case the same simulation is performed (i.e., remote fault and tripping of a transmission line) but this time at a weakened system condition, such that the effective short circuit ratio (SCR) at the IBR terminals has dropped to below 3. In this case we see that:

- REGC_A exhibits numerical instability during the fault – the software programs continuously complain that the network solution did not converge during the fault and for a short period after the fault clears.
- REGC_B behaves reasonably well numerically.
- REGC_C behaves well numerically, however, indicates that the high-gain PLL and inner-current control loops may result in an unstable recovery from the fault.

The EMT simulation results show us that the case is not unstable, but it is quite oscillatory and on the potential verge of instability. Thus, if the PLL and inner-current control loop gains are reduced, the case would behave much better.

All this simply illustrates the following facts:

1. REGC_A and REGC_B, being much simpler models, are quite adequate for modeling an IBR for network connection points that are quite strong (e.g., SCR > 3 or 4)
2. REGC_C can be utilized to investigate weakened system conditions, or for IBR being connected to weak grid nodes in order to identify if there is a need to further detailed (e.g., EMT) type evaluation. Once any issues are identified and resolved in an EMT environment, and the IBR is shown to perform well dynamically with proper retuning of the PLL and inner-current loop controls, the positive-sequence model can be tuned using either REGC_B or REGC_C to perform well and then be used in large scale stability studies.

[8] W. Baker and D. Ramasubramanian, Generic Photovoltaic Inverter Model in an Electromagnetic Transients Simulator for Transmission Connected Plants, June 2022, EPRI Report. Principal Investigator: J. Boemer. PV-MOD Milestone 2.7.3 https://epri.app.box.com/v/pvmod-milestone-2-7-3

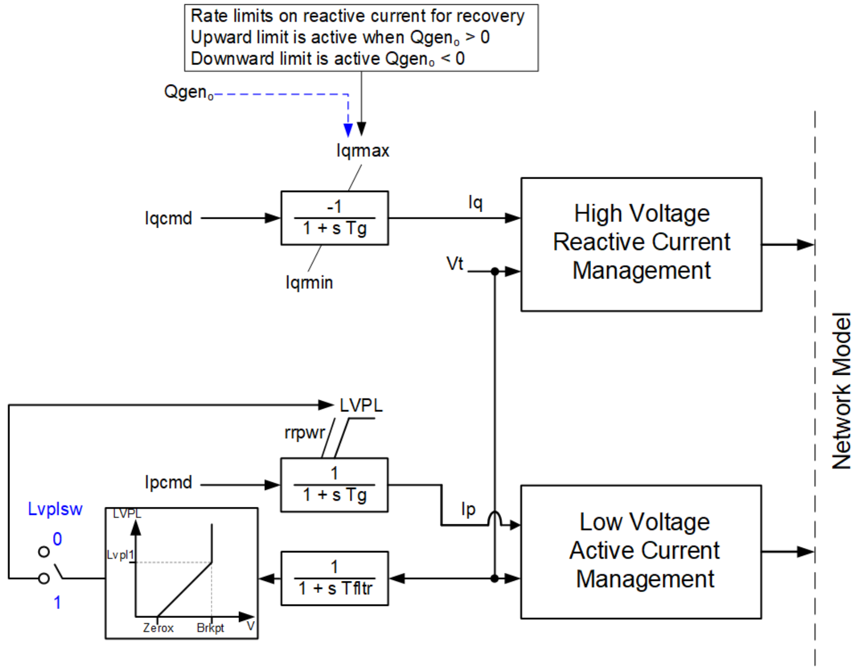


Figure 4-1
REGC_A Model

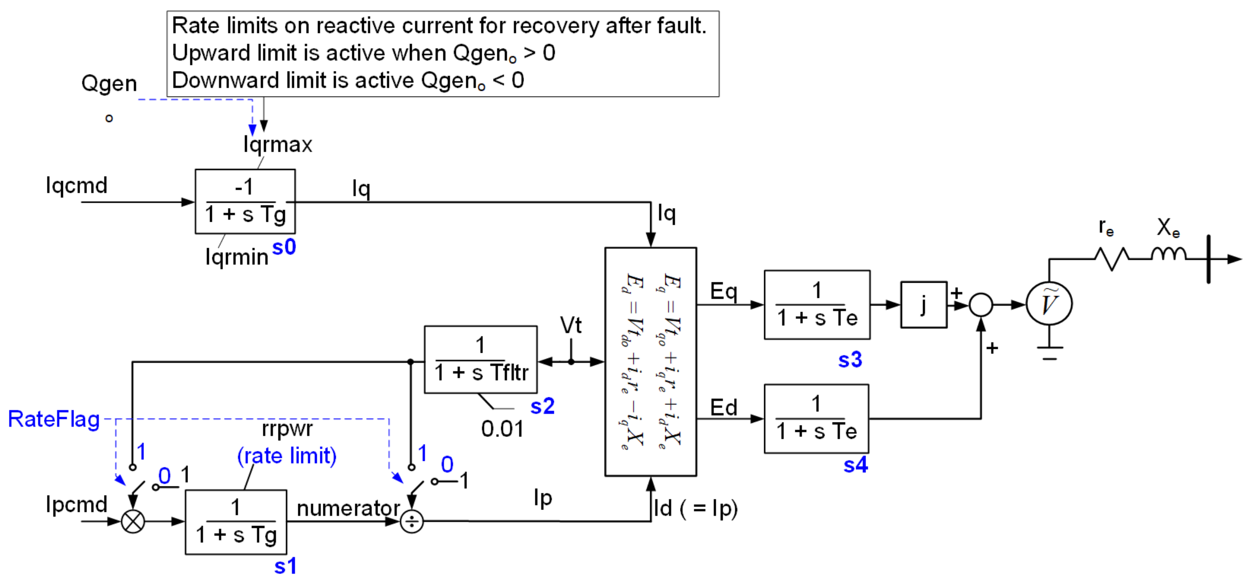


Figure 4-2
REGC_B Model

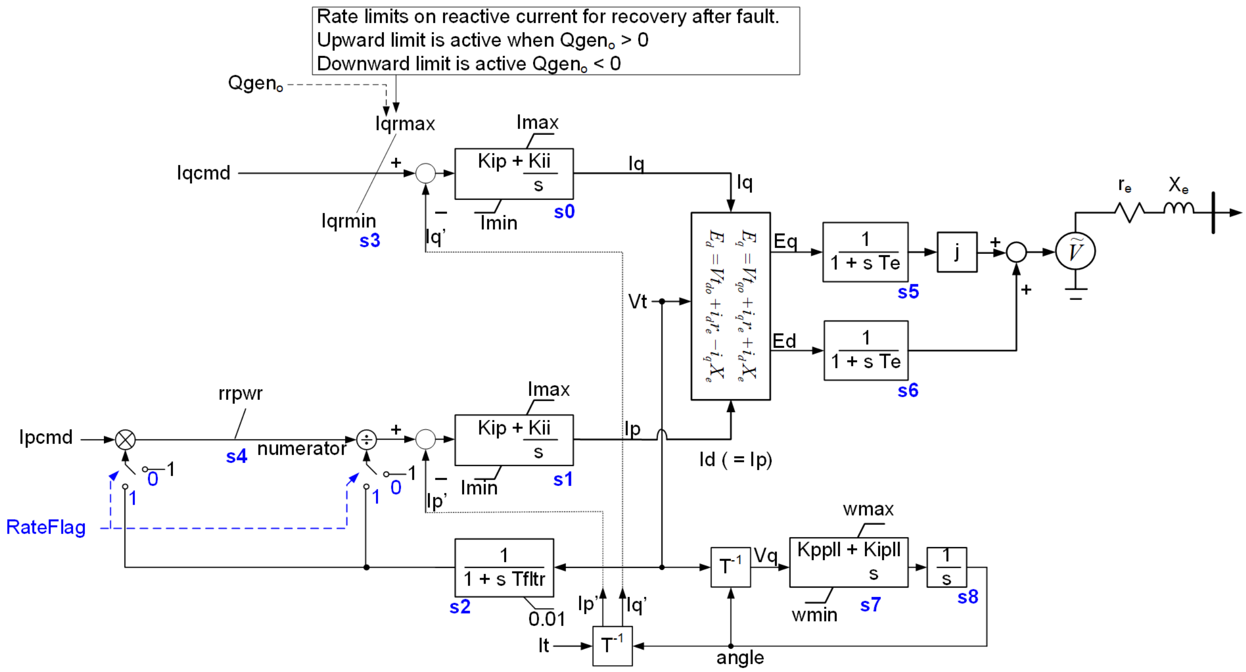


Figure 4-3
REGC_C Model

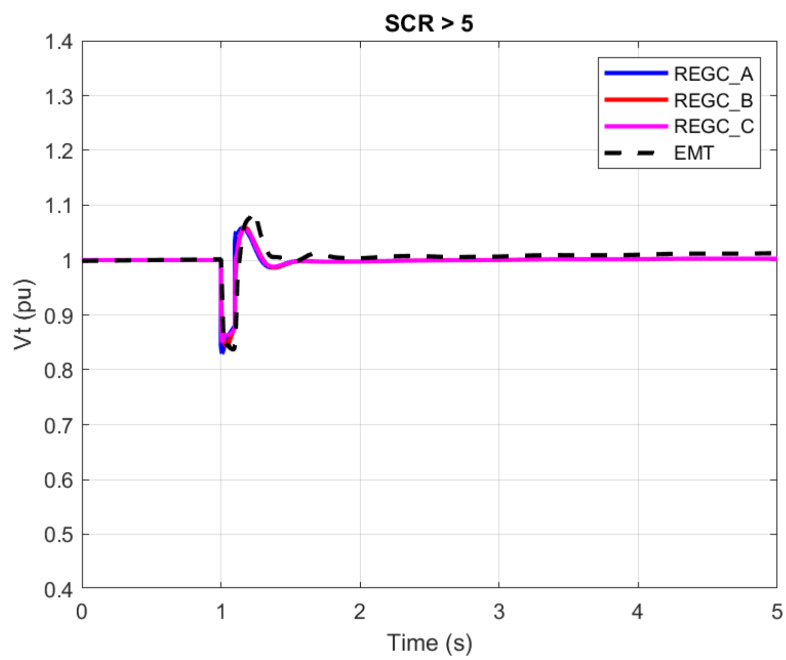


Figure 4-4
Example simulation of REGC_* models for a remote fault.

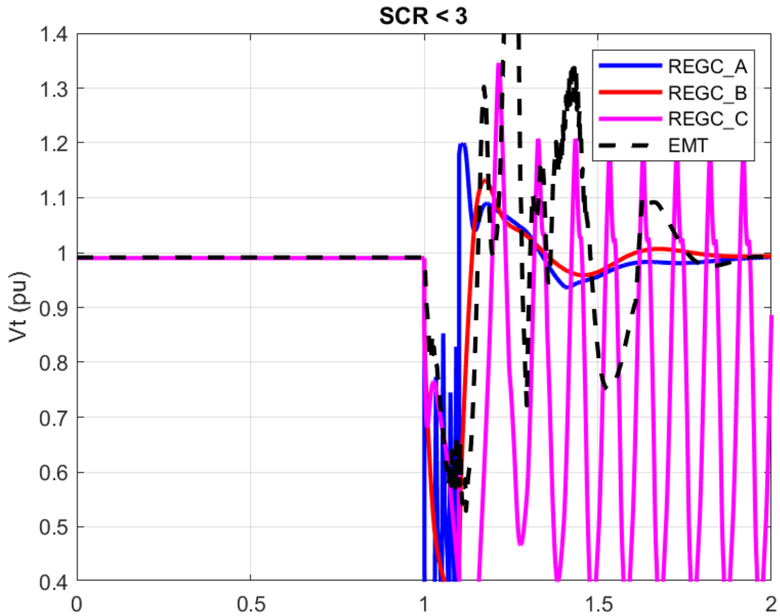


Figure 4-5
Example simulation of REGC_* models for a remote fault, for a weakened system condition.

Table 4-2
Parameter list for the REGC_* models

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	REGC_A	REGC_B	REGC_C
1	lvplsw	A flag set according to OEM instructions to turn on (1) or off (0) the LVPL curve	0	0	1	flag	√		
2	brkpt	Used only when Lvplsw = 1; voltage point below which active current is linearly reduced as a function of voltage until it reaches zero at zerox	0.05	0.9	0.9	[pu]	√		
3	zerox	Used only when Lvplsw = 1; voltage point below which active current become zero	0.01	0.4	0.5	[pu]	√		
3	lvpl1	Active current limit at Brkpt voltage and above	1.1	1.22	1.5	[pu]	√		
4	vtmax	These parameters are associated with the numerical interface between the current source and the network equiations. They are for maintaining numerical stability and convergence of the network solution. They should not be set to zero. Also, vtmax and qmin should not be confused with the maximum voltage and minimum reactive power that they device can produce in the continous operating range. These are related to numerical solutions at the transient limits - see High Voltage Reactive Current Management logic in the software manuals.	1.1	1.2	1.3	[pu]	√		
5	lvpnt1		0.05	0.8	0.9	[pu]	√		
6	lvpnt0		0.01	0.4	0.5	[pu]	√		
7	qmin		-1.3	-1.3	-1	[pu]	√		
8	accel	This is an acceleration factor for the numerical solution of the network interface to help with network convergence	0.1	0.7	1	N/A	√		
9	rrpwr	Rate of increase of active current after fault clearing	1	10	20	[pu/s]	√	√	√
10	tg	Converter controls delay emulation time-constant	0.017	0.02	0.05	[s]	√	√	
11	tfltr	Voltage measurement transducer filter time-constant	0.017	0.02	0.05	[s]	√	√	√
12	iqrmax	Upward rate limit on reactive current command	OEM	999	999	[pu/s]	√	√	√
13	iqrmin	Downward rate limit on reactive current command	OEM	-999	-999	[pu/s]	√	√	√
14	xe	Source reactance	0	OEM	0.25	[pu]	√	√	√
15	re	Source resistance	0	OEM	0.01	[pu]		√	√
16	te	Converter firing delay emulation time-constant	0.005	0.0083	0.02	[s]		√	√
17	rateflg	Rate limit flag (0) means that rrpwr is an active current rate limit, and (1) mean that rrpwr is interpreted as an active power rate limit	0	1	1	flag		√	√
18	dqflag	P/Q priority flag (0) mean Q priority, and (1) means P priority	0	0	1	flag		√	√
19	imax	Maximum continuous converter current rating	1	OEM	1.5	[pu]		√	√
20	kip	Proportional gain of the inner-current control loops	OEM	OEM	OEM	[pu/pu]			√
21	kii	Integral gain of the inner-current control loops	OEM	OEM	OEM	[pu/pu.s^{-1}]			√
22	kppll	Proportional gain of phase-locked loop	OEM	OEM	OEM	[rad.s^{-1}/pu]			√
23	kipll	Integral gain of the phase-locked loop	OEM	OEM	OEM	[rad.s^{-1}/pu.s^{-1}]			√
24	wmax	Phase-locked loop maximum output	OEM	OEM	OEM	[rad.s^{-1}]			√
25	wmin	Phase-locked loop minimum output	OEM	OEM	OEM	[rad.s^{-1}]			√
26	vdip	When filtered voltage is below vdip, freeze the PPL state	0.1	OEM	0.85	[pu]			√

Note: where a parameter range is designated by “OEM” is meant that there is no typical value or range that can be truly given. In the end, for any actual proposed or built project the value of all the parameters should come from the OEM, parameterized to the extent possible to match the actual equipment. However, here some typical, and range of values, have been provided simply for guidance. The range of values are not to be interpreted as absolute limits on the values of parameters.

4.2 Renewable Energy Electrical Controls Models

There are presently three (3) Renewable Energy Electrical Controls[9] (REEC) models:

1. REEC_A – this is the original model developed and first released around 2014 in commercial tools [1]. This was developed primarily for type 3 and 4 WTGs. It can also be used for PV, however, REEC_D has more features and thus perhaps is better suited for PV.
2. REEC_C – this model was developed in 2015 for the purpose of modeling battery energy storage systems (BESS) [7]. This model is very similar to REEC_A, with two major differences. First of all the model removes some of the complexity around the switching logic for current injection during a fault, as much of this was developed in REEC_A related to WTGs [4], [5]. Secondly, REEC_C includes a simple model for the charging and discharging of the battery to allow for modeling the state of charge (SOC) of the battery.
3. REEC_D – this model was developed in 2018, and after some revisions first released in the commercial tools around 2022. It is quite similar to the previous two models above, however, it incorporates several added features and updates based on feedback from several equipment vendors, and also allows for modeling BESS as well and WTGs and PV. The simple model for the charging and discharging of the battery, which is included in REEC_C, was removed. This is because, almost without exception, all BESS applications in power systems incorporate batteries that will allow for many minutes to hours of energy storage. As such, the SOC of the battery takes many tens of minutes to change significantly. Since the models developed here are primarily for use in bulk power system stability studies, which typically span a time period of tens of seconds to a maximum of one minute, modeling the SOC of the battery is not pertinent to such studies. That is, for simulation that are focused on a few tens of seconds of analysis to look at system stability, the SOC of the battery may be assumed to be constant.

The block diagram for all three are shown in Figure 4-6, Figure 4-7 and Figure 4-8, respectively.

[9] Another model called REEC_B was develop around 2015 by WECC's then Renewable Energy Modeling Task Force. It has since been removed from the WECC approved model list, and also discouraged by NERC. The model was too simple and did not allow for modeling the inverter-blocking and other features, which are now included in REEC_D. Thus, we are not covering REEC_B in this document.

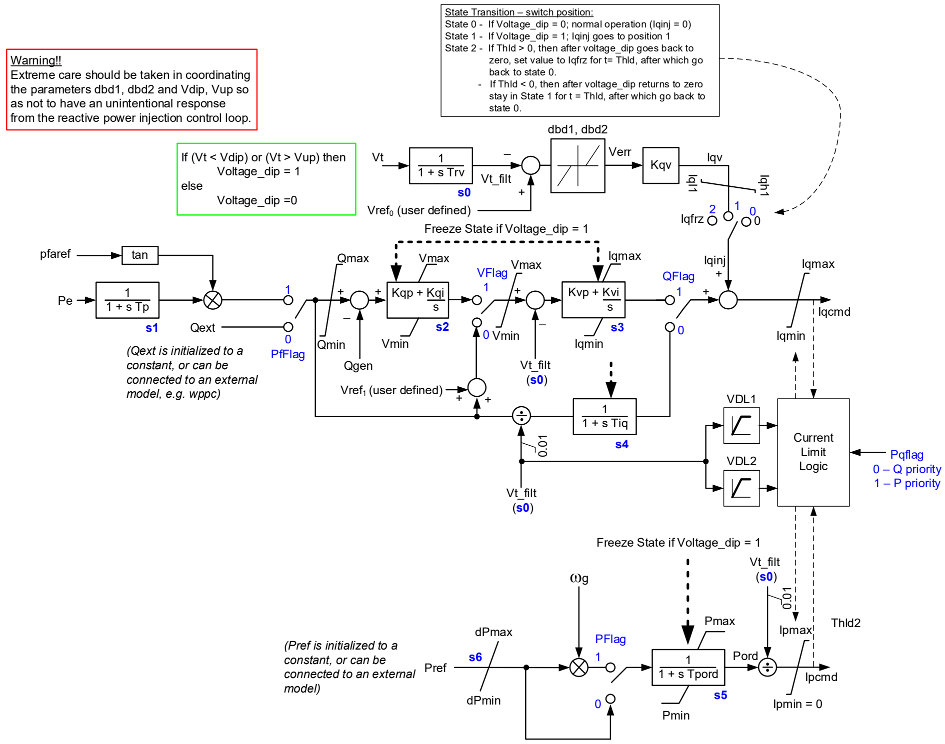


Figure 4-6
REEC_A Model

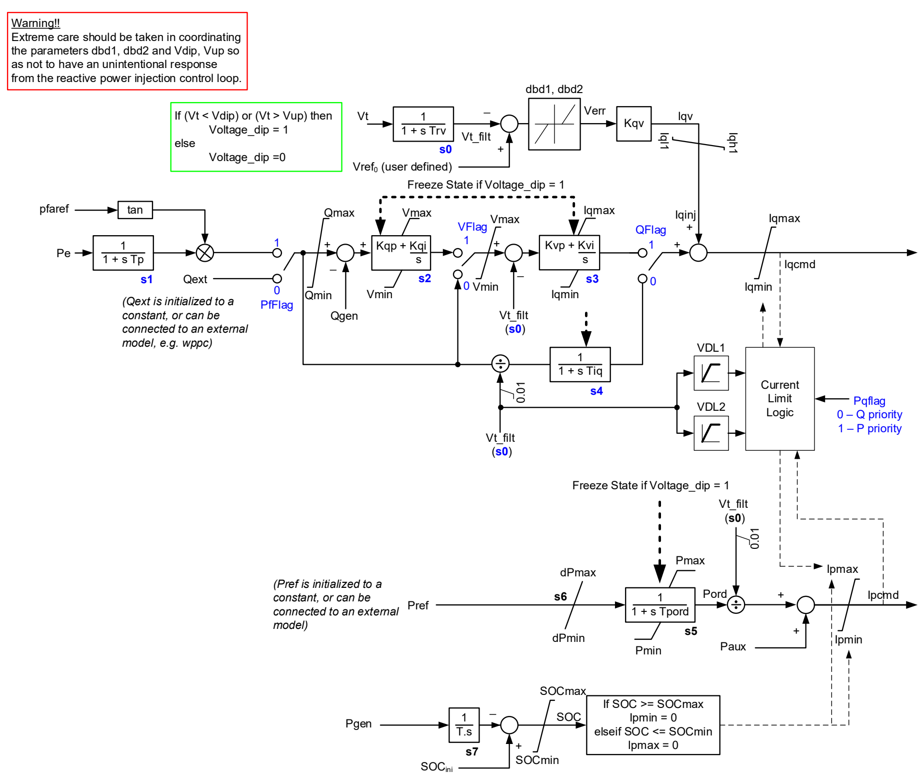


Figure 4-7
REEC_C Model

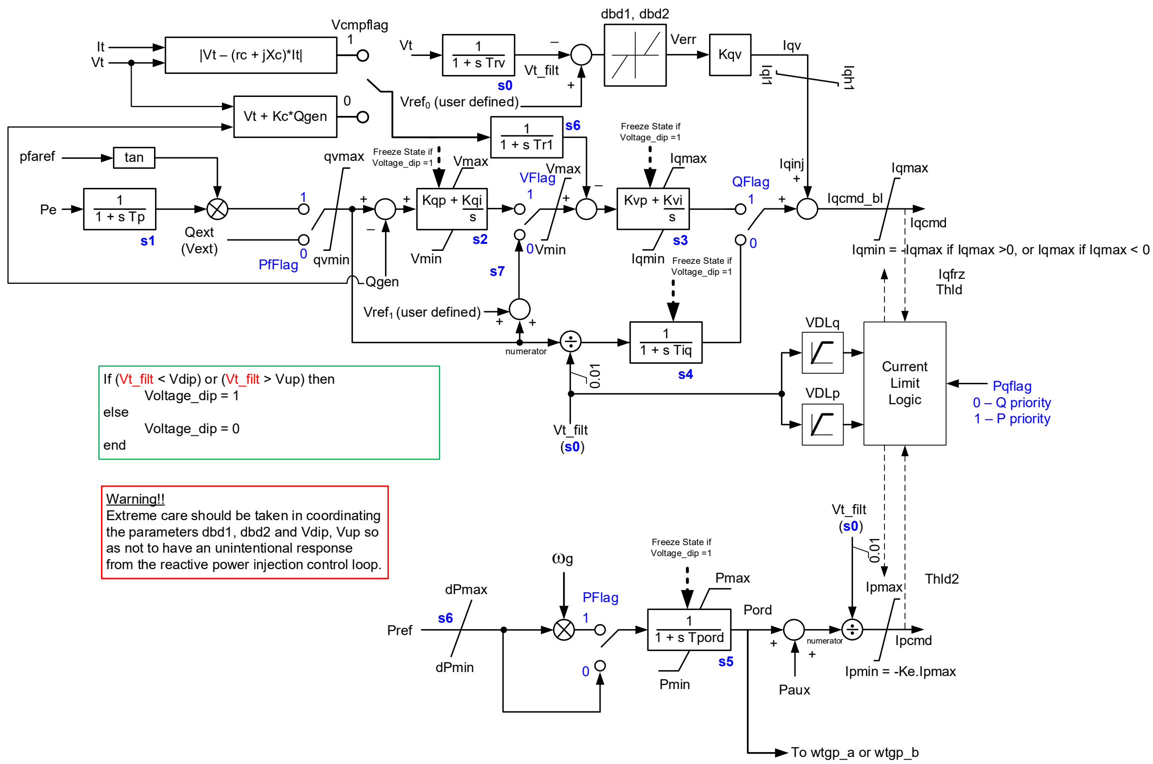


Figure 4-8
REEC_D Model

All of these models have a common feature in that there are three (3) main parts to the model:

- active current controls which develop the active current command *Ipcmd,*
- reactive current controls which develop the reactive current command *Iqcmd*, and
- the converter current limit logic which limits the active and reactive current to within the ratings of the converter[10]

Let us use REEC_A to explain these three functions. Thereafter, an explanation will be given on the differences between the three models.

Reactive Power Control

Consider Figure 4-9 and Table 4-3, both these show that there are essentially four (4) paths for reactive current (power) control, namely:

- Local constant Q control – *PfFlag* = 0 and *QFlag* = 0; *VFlag* = 1 or 0 (irrelevant)
- Local constant power factor (pf) control – *PfFlag* = 1 and *QFlag* = 0; *VFlag* = 1 or 0 (irrelevant)
- Local terminal voltage control – *PfFlag* = 0, *VFlag* = 0 and *QFlag* = 1

[10] The current limit logic is shown in Appendix B. It assumes a full-converter unit. For the sake of simplicity, it was decided, during the development of these models, by the WECC group to not make a distinction between stator current limits for the type 3 WTG and converter current limits for the type 4 WTG/PV/BESS.

- Local coordinated Q/V control – *PfFlag* = 0, *VFlag* = 1 and *QFlag* = 1

In addition to the above, there is a separate proportional, with deadband, current injection control which can be used either as proportional voltage control during a voltage dip (deadband set to zero) or a proportional current injection with deadband during a voltage dip. To disable this path, *Kqv* can be set to zero, or *Vup* and *Vdip* set to, for example, 2 and 0, respectively. The parameters *Iqfrz* and *Thld* can be used in association with this current injection loop to create various state transitions, as shown in Figure 4-10. These state transitions were implemented to accommodate various original equipment manufacturer (OEM) requests during the model development process. The user should use these only as instructed by OEMs or if the user clearly understands their implications. There is also a parameter, *Thld2*, which when set to a non-zero value will hold the active current command (*Ipcmd*) at the value it has been frozen at during a voltage dip, after the fault clears. That is, when *Voltage_dip = 1*, the active current command will be frozen to a given value. If *Thld2* were set to for example 0.1 s, then once the disturbance is over and *Voltage_dip =0*, the value of the active current command remains at its frozen value for another 0.1s, before being released.

For the local voltage control option, the user-defined reference bias *Vref1* is typically set to the default value of zero (0). This bias was provided again at the request of one OEM. It should only be used if so instructed, otherwise we advise always setting it to zero.

Active Power Control

The active power control path is relatively simple. It is essentially a straight pass through from the upstream plant controller through the electrical controls to the generator/converter. There is a single time-constant and a set of limits to emulate the control delay and limits. The only other aspect is the flag *PFlag*. For type 3 WTGs *PFlag* should be 0, because in all of the commercial software tool implementations of these models the effect of the power developed by the turbine being modulated by perturbations in the shaft speed, since the electrical generator is directly coupled to the grid, is emulated in the torque controller (WTGQ_A) model. That is the torque controller model develops electrical torque, and at the output of the model torque times speed yields power which is then fed into this model (see section 4.4.4).

For type 4 WTGs either option may be valid depending on the type of unit. For a type 4A WTG the electrical power output of the unit is perturbed by the torsional oscillations of the turbine-generator shaft (see [5] for example validation cases) and so *PFlag* can be set to 1 and the WTGT_B model should be used to approximately emulate this behavior[11]. For type 4B WTGs there is no appreciable observation of electrical power perturbation due to torsional oscillations in the turbine generator shaft, due to the converter design, and so *PFlag* is set to 0 and no WTGT_B model used.

---

[11] The WTGT_B model when used with the type 4 WTG is intended solely for emulating the observed torsional oscillations post-fault in some type 4 equipment, where this occurs. This model was recently developed (released first in 2021-2022) to better capture the response for a type 4 WTG where the entire mechanical side is not modeled. As explain in a later section, this model now does capture the variation of mechanical power, through a simple time-constant. This model should not be used with type 3 WTGs where the entire mechanical system is modeled.

The rest of the parameters associated with the active power control are the maximum and minimum power ratings of the unit (*Pmax/Pmin*), the maximum and minimum rate of change of power reference (*dPmax/dPmin*) and the time constant associated with the controls (*Tpord*).

Since this model is for use with WTGs (or PV) the minimum active current command is clearly zero (*Ipmin = 0*), and this is not changeable by the user. Thus, this model is not suitable for BESS.

The maximum active current command limit is determined by the current limit logic (*Ipmax*).

Table 4-3
Reactive power control modes for the REEC_A model.

Control Mode	PfFlag	VFlag	QFlag
Local constant Q control	0	0 or 1	0
Local constant power factor (pf) contorl	1	0 or 1	0
Local voltage control	0	0	1
Local coordinated Q/V control	0	1	1

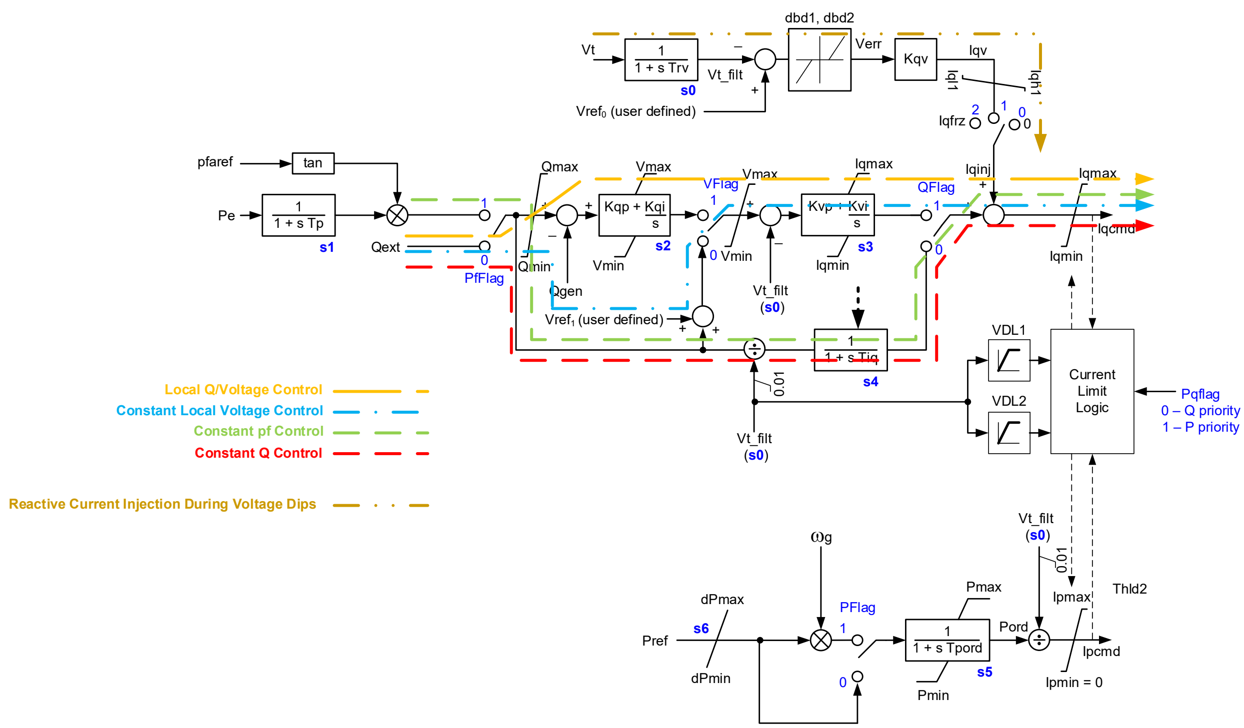


Figure 4-9
Options for the reactive power control path in the REEC_A model.

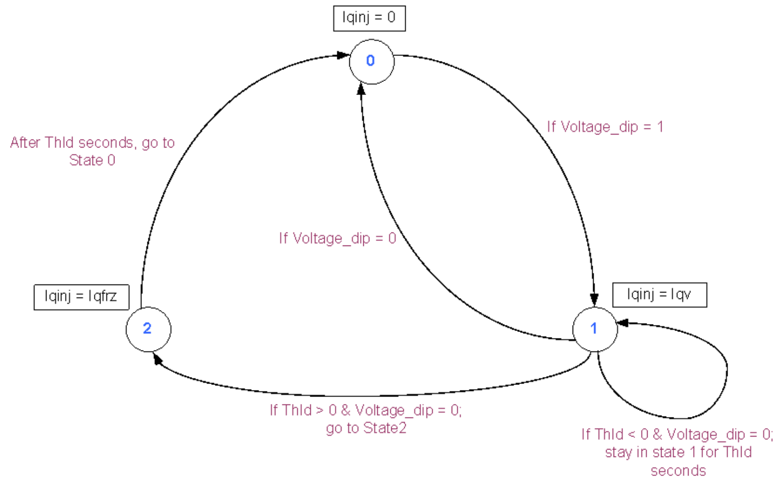


Figure 4-10
State transition diagram for the REEC_A model reactive current injection during a voltage-dip.

Current Limit Logic

The current limit logic implementation is given in Appendix A. In its most basic form the current limit is a semi-circle around quadrants 1 and 4, as shown in Figure 4-11. That is, only positive active current is allowed (Ipmin = 0) since this is a model for a generator, and the total current must be less than or equal to Imax. The selection of the Pqflag determines whether priority is given to active or reactive current. The VDL1 and VDL2 tables are two look-up tables with four pairs of numbers that define a piece-wise linear curve. These tables define the reactive and active current limits, respectively, as a function of voltage. Therefore, in addition to the basic current limit shown in Figure 4-11, the voltage-dependent limit (VDL) tables can be used to effect further limits on either active or reactive current as a function of voltage. The values of these tables need to come either directly from the OEM or based on fitting the values from factory (or field tests) that clearly show the reactive and active power output of a single WTG (or PV) as a function of various voltage dips. To disable these tables (or if data is not available) then simply set all the values to Imax for four different voltage settings, e.g. Vq1 = 0, Iq1 = Imax; Vq2 = 0.2; Iq2 = Imax; Vq3 = 0.5, Iq3 = Imax and Vq4 = 1.0, Iq4 = Imax etc. The tables could also be used to effect limiting (reducing) reactive output at high voltage levels. Since the original release of these models, it has become apparent that there would be great benefit to having a significantly larger number of point in these tables (more than four). As such, the REEC_D model (Figure 4-8) was recently developed in which the VDL tables each have ten (10) pairs of points for greater flexibility.

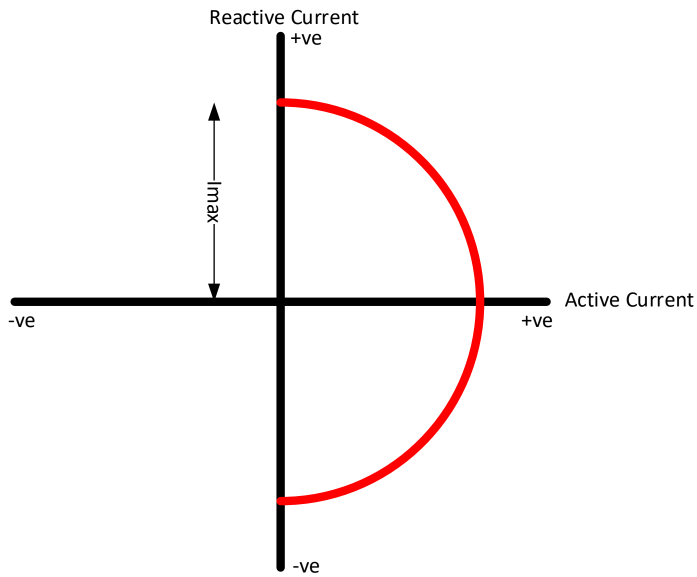


Figure 4-11
Current limit for REEC_A model.

Additional Features of REEC_C and REEC_D

Consider the REEC_C model shown in Figure 4-7. The differences between this model and the REEC_A model (Figure 4-6) are as follows:

1. It does not have the parameters and functionality of the REEC_A model associated with the state-transitions around the reactive current injection path shown in Figure 4-10. The reactive current injection path is always active, unless the gain is set to zero, or the deadband made extremely wide.
2. The active power path cannot be modulated by speed and so this model cannot be used with the WTGT_A or WTGT_B models. In essence, it should not be used for modeling WTGs.
3. It contains an additional path with a simple representation for a battery charging/discharging mechanism. Thus, the model is primarily intended for use in modeling BESS.
4. The minimum active current (Ipmin) is equal to –Ipmax; that is, the model allows power to be both generated and absorbed, and therefore can be used to model energy storage.

Other than the above points, the model is identical to REEC_A. Let us consider in more detail the charging/discharging feature of this model. This additional part of the model is shown in Figure 4-12. This added feature has the following key aspects:

1. A user defined parameter which specifies the initial state of charge (*SOC*) of the battery. This tells the model how much charge the battery has prior to starting the simulation.
2. A representation of the maximum and minimum allowable state of charge (*SOCmax* and *SOCmin*). Most battery OEMs recommend that the battery not be left in a state of full-charge or full-discharge in order to preserve the battery's longevity and performance. The model simulates this through the user specified values for the maximum (*SOCmax*) and minimum (*SOCmin*) allowed state of charge during operation. Many vendors recommend operating the batteries within a range of 20% to 80% state of charge.

3. The simple integrator block, with the time constant *T*, represents the process of charging and discharging. The level of charge in the battery is proportional to stored energy. Energy is the time integral of power since power is specified in units of watts = joules (energy) per second. Thus, by integrating the power coming out of (or going into when charging) the device, we get a representation of the state of charge.
4. The logic block at the end of the model represents the action of collapsing the output of the converter (i.e. forcing its active current output) to zero once the maximum or minimum state of charge has been reached. So, for example, if the *SOC* is greater than the allowable *SOCmax*, then *Ipmin* is forced to zero, meaning that the battery cannot absorb/store any more electrical energy.

Consider a simple example of how the REEC_C model might be parameterized to represent a BESS. Assume we have a BESS that is rated at 40 MVA, with an energy rating of 30 MWh for 4 hours. Also, let us assume that when in operation the BESS is required by the vendor to always be in a state of charge between 20% to 80%, with the same charging rate (i.e. 4 hours).

Then,

SOCmax = 0.8

SOCmin = 0.2

The total energy of the device = 30×4 = 120 MWh, thus in operation it can go from 0.8×120 (96 MWh) to 0.2×120 (24 MWh), which means that the maximum output would be (96 – 24)/4 = 18 MWh for 4 hours.

Therefore,

T = ((18/30) × (60×60×4)) / (0.8 – 0.2) = 14,400

Pmax = 18/30 = 0.6

Pmin = - Pmax = -0.6

Imax = 40/30 = 1.33

The model MVA = 30 MVA. All other parameters would be set per the OEM data.

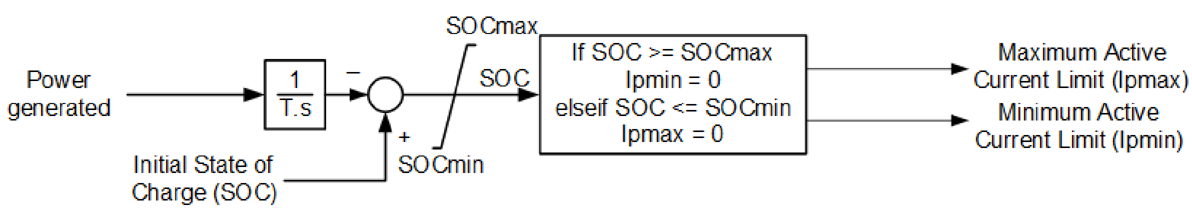


Figure 4-12
Extra part of the *reec_c* model for simulating charging and discharging of a storage mechanism.

One example of a more detailed account of modeling battery energy storage with these generic models, and a comparison of the performance of the generic models to detailed proprietary 3-phase models can be found in [19].

Consider the REEC_D model shown in Figure 4-8. The differences between this model and the REEC_A model (Figure 4-6) are more extensive, and were based on feedback from several

OEMs. Based on the feedback several new features and extensions were added to develop REEC_D [9]. These differences are as follows:

1. The VDL tables in REEC_D have ten (10) pairs of points, to give greater flexibility. In addition, a new parameter *Ke* is introduced to allow for modeling of energy storage. The details of all this are explained in Appendix B.
2. The addition of two new blocks:
   - A local current-compensation block ($|Vt - (rc + jXc).It|$) with a lag block to emulate measurement delays (*Tr1*). The lag block time-constant (*Tr1*) can be set to zero. Likewise, *rc* and *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.
   - A local reactive-droop compensation block (*Kc*) with a lag block to emulate measurement delays (*Tr1*). The lag block time-constant (*Tr1*) 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 (*Qgen*) voltage of the generator/converter model (REGC_*) which is downstream of this model.
3. The reactive-current injection arm (which has the output *Iqinj*), 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 (i.e., what is shown in Figure 4-10 does not exist in this model). 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* and *Vup* set to e.g., -1 and 2 to completely turn-off the voltage-dip logic. The two parameters *Iqfrz* and *Thld* remain, but now have a slightly different function. The logic is as follows:
   - If *Thld* = 0 – no other action is taken.
   - If *Thld* > 0, then for *Thld* seconds following a voltage dip (i.e. *voltage_dip* goes from 1 back to 0) *Iqcmd_bl* is held at its current value (i.e. value just prior to the end of the *voltage_dip*) for *Thld* seconds and is then released.
   - If *Thld* < 0, then for *Thld* seconds following a voltage dip (i.e. *voltage_dip* goes from 1 back to 0) *Iqcmd_bl* is held equal to *Iqfrz* for *Thld* seconds and is then released.

     Note: The value of *Iqcmd_bl* that is held/frozen is the value that is after the summing junction and just before the *Iqmax/Iqmin* limits as shown in Figure 4-8.

     In addition to the above, the REEC_D also has logic that holds/freezes active current command (and active current *Ipmax*) at the previous value (i.e. at the value that they both were at during the *voltage-dip* and just prior to the release of the *voltage dip*) for *Thld2* seconds following a voltage dip, i.e. *voltage_dip* goes from 1 back to 0.
4. Blocking Logic: At very low voltages at the terminals of the converter the converter power electronics 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 *VDL* 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:

- *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 11) is less than or equal to *vblkl* then *Iqmax* and *Ipmax* are forced to 0 (i.e. *Iqmax = Ipmax = Iqmin = Ipmin = 0*, and thus both the *Ipcmd* and *Iqcmd* = 0).
- *vblkh* – this is the voltage above which the converter will block. That is, if the measured terminal voltage of the generating device (*Vt_filt*) is greater than or equal to *vblkh* then *Iqmax* and *Ipmax* are forced to 0 (i.e. *Iqmax = Ipmax = Iqmin = Ipmin = 0*, and thus both the *Ipcmd* and *Iqcmd* = 0).
- *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. *Iqmax = Ipmax = Iqmin = Ipmin = 0* for another *Tblk_delay* seconds after the voltage recovers outside of the blocking range).
- A final feature of this blocking mechanism is that in the commercial software tools that have adopted this model, and the new generator/converter models REGC_B and REGC_C, a "link" is established inside the software platforms between these models that comes from the REEC_D model and directly tells the generator (REGC_B or REGC_C) to block, i.e. to set active and reactive current coming out of the generator/converter to "zero" the instant blocking is invoked in REEC_D.

5. <u>The addition of *Paux*:</u> The new input *Paux* was added to be accessible both by the user for manipulation by an external user-written model, or by the auxiliary control model discussed below in section 4.4.6.
6. <u>Filter Time Constant:</u> Note that now *voltage_dip* is determined from the filtered (*Vt_filt*) voltage rather than *Vt*.
7. This model also follows the so-called *baseload flag* that is used in the major North American software tools. Namely,
   - If baseload flag = 0, then the model behaves normally,
   - If baseload flag = 1, then *Pmax* = initial power flow MW output of the plant ($Pgen_o$) and thus the power order can only go down and not up, and
   - If baseload flag = 2, then $Pmax=Pmin = Pgen_o$ and thus the power order is fixed.

Finally, all input references (i.e. *Vref0, pfaref, Vref1, Pref, Qext* and *Paux*) 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 (REPC_*) then *Qext* and *Pref* will be controlled by that model and cannot be also controlled by another user-written model.

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. To that end, when REEC_D was proposed, a standard way of modeling the non-windup limits was suggested [9]. None-the-less, in the end the choice of implementation of the non-windup limit will be on the software vendor and so some subtle differences might be seen across software platforms for onerous cases. See [9] for a more detailed discussion on the non-windup limits.

The complete parameter list for the REEC_* models is provided in Table 4-4, together with a description of each parameter and the suggested range of each parameter and the typical value. Once again it should be understood that the range of each parameter value, and the suggested typical value of each parameter, as presented in Table 4-4 is simply for the purposes of providing some initial guidance. They are not to be taken as absolute limits on the possible values of the parameters. There may be perfectly legitimate values for the parameters, when the model is properly parameterized for a specific purpose, that are outside of the suggested range of values. Care must always be taken to properly, and meaningfully, parameterize the models, and if modeling an actual project to consult the OEM.

Table 4-4
Parameter list for the REEC_* models

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	REEC_A	REEC_C	REEC_D
1	vdip	**<u>Note:</u> to disable vdip it is typical to set it to -1;** The voltage below which voltage-dip logic is initiated	-1	0.9	0.95	[pu]	√	√	√
2	vup	**<u>Note:</u> to disable vup it is typical to set it to 2;** The voltage above which voltage-dip/up logic is initiated	1.05	1.1	2	[pu]	√	√	√
3	trv	Voltage measurement transducer time constant	0	0.02	0.1	[pu]	√	√	√
4	dbd1	Lower deadband in voltage error	-0.15	OEM	0	[pu]	√	√	√
5	dbd2	Upper deadband in voltage error	0	OEM	0.15	[pu]	√	√	√
6	kqv	Reactive current injection proportional gain; active only during a voltage-dip/rise; 0 to disable	0	OEM	5	[pu]	√	√	√
7	iqh1	Maximum limit on reactive current injection during a voltage-dip/rise	0.1	1	Imax	[pu]	√	√	√
8	iql1	Minimum limit on reactive current injection during a voltage-dip/rise	-Imax	-1	-0.1	[pu]	√	√	√
9	vref0	If *vref0* is left as zero most commercial software tools will initialize it appropriately; otherwise typically set to 1 pu (nominal voltage)	0	0	0	[pu]	√	√	√
10	iqfrz	The logic associated with these parameters is different between REEC_A and REEC_D. See main report text. <u>In brief summary:</u> (i) for REEC_A see Figure 11, (ii) for REEC_D if thld > 0 then Iqcmd is held at its value at the end of a voltage dip for thld seconds after a voltage dip, if thld < 0 then Iqcmd is held at iqfrz at the end of a voltage dip for thld seconds. For both models, if thld2 > 0, Ipcmd is held for thld2 seconds to the value it has at the end of the voltage dip.	0	0	OEM	[pu]	√		√
11	thld		0	0	OEM	[s]	√		√
12	thld2		0	0	OEM	[s]	√		√
13	tp	Electrical power measurement transducer time constant	0	0.02	0.1	[s]	√	√	√
14	qmax	Maximum reactive output limit (to disable set to 9999)	OEM	OEM	9999	[pu]	√	√	√
15	qmin	Minimum reactive output limit (to disable set to -9999)	-9999	OEM	OEM	[pu]	√	√	√
16	vmax	Voltage control maximum limit; typically 110% (higher values than shown may be used in some cases)	1.05	1.1	1.1	[pu]	√	√	√
17	vmin	Voltage control minimum limit; typically 90% (lower values than shown may be used in some cases)	0.9	0.9	0.95	[pu]	√	√	√
18	kqp	These are tunable PI gains of the local q-control	OEM	OEM	OEM	[pu/pu]	√	√	√
19	kqi		OEM	OEM	OEM	[pu/pu/s]	√	√	√
20	kvp	These are tunable PI gains of the local v-control	OEM	OEM	OEM	[pu/pu]	√	√	√
21	kvi		OEM	OEM	OEM	[pu/pu/s]	√	√	√
22	vref1	Typically set to zero; only change if instructed by OEM data	0	0	OEM	[pu]	√	√	√
23	tiq	Controller time-constant	0.01	0.02	0.1	[s]	√	√	√
24	dpmax	Up ramp-rate on power reference; typically set to 999 to disable	0.1	999	999	[pu/s]	√	√	√
25	dpmin	Down ramp-rate on power reference; typically set to -999 to disable	-999	-999	-0.1	[pu/s]	√	√	√
26	pmax	Maximum power reference (high values than shown may be used in some cases)	1	1	1.15	[pu]	√	√	√
27	pmin	Minimum power reference - **should NOT be negative for REEC_A; can be negatrive for REEC_C and REEC_D when modeling storage**	-1	0	0.05	[pu]	√	√	√
28	imax	Maximum current limit of the device	1	OEM	1.2	[pu]	√	√	√
29	tpord	Time constant for power order	0.01	0.02	0.1	[pu]	√	√	√
30	pfflag	Depends on actual control strategy. Obtain from OEM based on actual controls.	0	OEM	1	N/A	√	√	√
31	vflag		0	OEM	1	N/A	√	√	√
32	qflag		0	OEM	1	N/A	√	√	√
33	pflag		0	OEM	1	N/A	√	√	√
34	pqflag		0	OEM	1	N/A	√	√	√

Table 4-4 (continued): Parameter list for the REEC_* models

35	vq1		OEM	OEM	OEM	[pu]	√	√	√
36	iq1		OEM	OEM	OEM	[pu]	√	√	√
37	vq2		OEM	OEM	OEM	[pu]	√	√	√
38	iq2		OEM	OEM	OEM	[pu]	√	√	√
39	vq3		OEM	OEM	OEM	[pu]	√	√	√
40	iq3		OEM	OEM	OEM	[pu]	√	√	√
41	vq4		OEM	OEM	OEM	[pu]	√	√	√
42	iq4		OEM	OEM	OEM	[pu]	√	√	√
43	vq5		OEM	OEM	OEM	[pu]			√
44	iq5		OEM	OEM	OEM	[pu]			√
45	vq6		OEM	OEM	OEM	[pu]			√
46	iq6		OEM	OEM	OEM	[pu]			√
47	vq7		OEM	OEM	OEM	[pu]			√
48	iq7		OEM	OEM	OEM	[pu]			√
49	vq8		OEM	OEM	OEM	[pu]			√
50	iq8		OEM	OEM	OEM	[pu]			√
51	vq9		OEM	OEM	OEM	[pu]			√
52	iq9		OEM	OEM	OEM	[pu]			√
53	vq10		OEM	OEM	OEM	[pu]			√
54	iq10	These are the voltage-dependent limits on active and reactive current. There is no typical set of values. However, as they stand today, the following guidelines should be followed: (i) the values should generally be monotonically increasing, and (iii) to disable the block simply set all iq/ip values to Imax for a set of monotonically increases voltage values. <u>Recommendation:</u> use values from OEM data.	OEM	OEM	OEM	[pu]			√
55	vp1		OEM	OEM	OEM	[pu]	√	√	√
56	ip1		OEM	OEM	OEM	[pu]	√	√	√
57	vp2		OEM	OEM	OEM	[pu]	√	√	√
58	ip2		OEM	OEM	OEM	[pu]	√	√	√
59	vp3		OEM	OEM	OEM	[pu]	√	√	√
60	ip3		OEM	OEM	OEM	[pu]	√	√	√
61	vp4		OEM	OEM	OEM	[pu]	√	√	√
62	ip4		OEM	OEM	OEM	[pu]	√	√	√
63	vp5		OEM	OEM	OEM	[pu]			√
64	ip5		OEM	OEM	OEM	[pu]			√
65	vp6		OEM	OEM	OEM	[pu]			√
66	ip6		OEM	OEM	OEM	[pu]			√
67	vp7		OEM	OEM	OEM	[pu]			√
68	ip7		OEM	OEM	OEM	[pu]			√
69	vp8		OEM	OEM	OEM	[pu]			√
70	ip8		OEM	OEM	OEM	[pu]			√
71	vp9		OEM	OEM	OEM	[pu]			√
72	ip9		OEM	OEM	OEM	[pu]			√
73	vp10		OEM	OEM	OEM	[pu]			√
74	ip10		OEM	OEM	OEM	[pu]			√

Table 4-4 (continued): Parameter list for the REEC_* models

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	REEC_A	REEC_C	REEC_D
75	SOCini	Initial state of charge (SOC) of the battery	SOCmin	0.5	SOCmax	[pu]		√	
76	SOCmax	Maximum SOC of the battery	0.7	0.8	0.9	[pu]		√	
77	SOCmin	Minimum SOC of the battery	0.1	0.2	0.3	[pu]		√	
78	T	Charging/discharging time constant	Many 1000's of seconds			[s]		√	
79	vcmpflag	Type of compensation = 1 - current compensation or 0 reactive droop	0	0	1	flag			√
80	rc	Current compensation resistance	0	0	0.02	[pu]			√
81	xc	Current compensation reactance	0	0	0.15	[pu]			√
82	tr1	Filter time constant	0	0.02	0.5	[s]			√
83	kc	Reactive droop gain	0	0.05	0.15	[pu/pu]			√
84	ke	Scaling on the Ipmin: 0 < ke ≤ 1, set to 0 for generator and non-zero for a storage device	0	0	1	[pu]			√
85	vblkh	Voltage above which the converter will block	OEM	OEM	OEM	[pu]			√
86	vblkl	Voltage below which the converter will block	OEM	OEM	OEM	[pu]			√
87	tblkdelay	Time delay for unblocking after voltage recovers (vblk1 < vt_flt < vblkh)	0.04	0.04	0.1	[s]			√

Note: where a parameter range is designated by "OEM" is meant that there is no typical value or range that can be truly given. In the end, for any actual proposed or built project the value of all the parameters should come from the OEM, parameterized to the extent possible to match the actual equipment. However, here some typical, and range of values, have been provided simply for guidance. The range of values are not to be interpreted as absolute limits on the values of parameters.

4.3 Renewable Energy Plant Controls Models

There are presently two (2) main Renewable Energy Plant Controller (REPC) models:

- REPC_A – this is the original power plant controller (PPC) that was developed in the 2010 to 2013 timeframe and released first in the commercial software tools around 2014, with REGC_A and REEC_A. It is a simple PPC model that allows for either (i) voltage control with or without deadband and/or droop/current compensation at the point of measurement (POM) of the plant, or (ii) control reactive power control at the POM. It also allows for a simple asymmetrical droop-based primary frequency response (PFR) control at the POM.
- REPC_C – this is a newly developed PPC model that was developed around 2018 together with REEC_D. It was first released in commercial software tools around 2022. It has the same core structure of REPC_A, but adds several new features, based on feedback from several equipment vendors [9]. These new features are described in more detail below. In summary, they include (i) the ability to model constant power factor control at the POM, (ii) the ability to model coordinate shunt switching at the plants substation, (iii) the inclusion of several new limits and ram-rate limits across the model.'

Both of the above PPC models control a single aggregated downstream IBR unit. That is, each of the above PPC models can be used to control a single downstream REEC_* model. These two models are shown in Figure 4-13 and Figure 4-14, respectively.

To model a plant with multiple aggregated downstream IBR units (e.g. two aggregated wind turbine generators, or a hybrid-pant with PV and BESS, etc.) a PPC model is required which can be connected to multiple downstream generator models. Thus, in 2014/2015 an initial hybrid PPC model was developed, called REPC_B, which is still in use. However, this model has known limitations[12], and thus in 2022 a new PPC model – REPC_D – was proposed to address these limitations. The REPC_D is presently under development by the commercial software vendors and should hopefully be released in late 2023, or early 2024. A brief description of the model is provided here, and the tentative block diagram shown in Figure 4-15.

The REPC_A and REPC_C models connect directly to the REEC_* (electrical controls) models downstream for a type 4 WTG model, a PV model or a BESS model. For a type 3 WTG, the PPC interfaces with the torque controller in its active power path, and with the electrical controls model in its reactive power path. The general connection diagrams for a complete plant model are shown in section 4.4. Thus, both PPC models have two separate control paths (i) the reactive power control path, and (ii) the active power control path.

---

[12] See https://www.wecc.org/Reliability/Clarification%20on%20Proper%20Use%20of%20REPC%20models.pdf

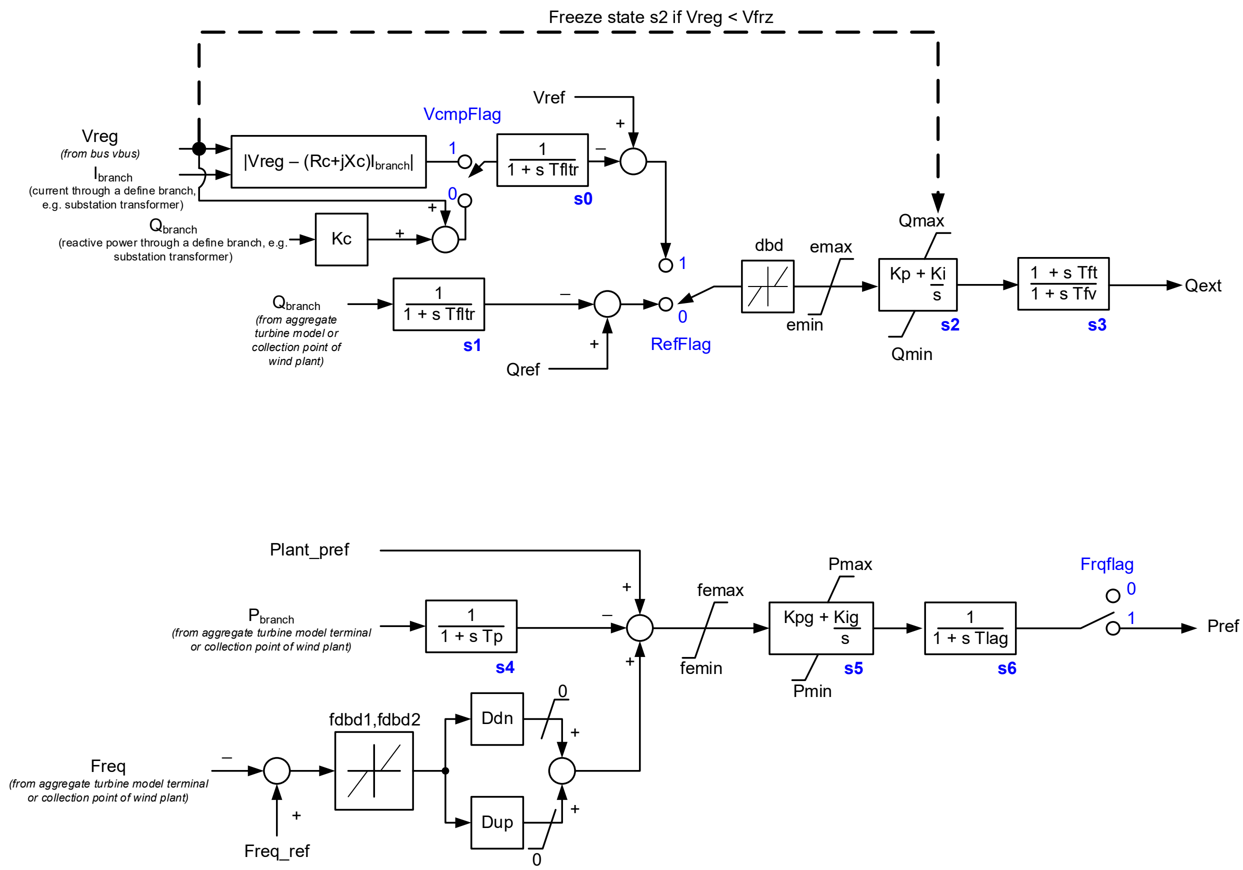


Figure 4-13
The REPC_A power plant controller model.

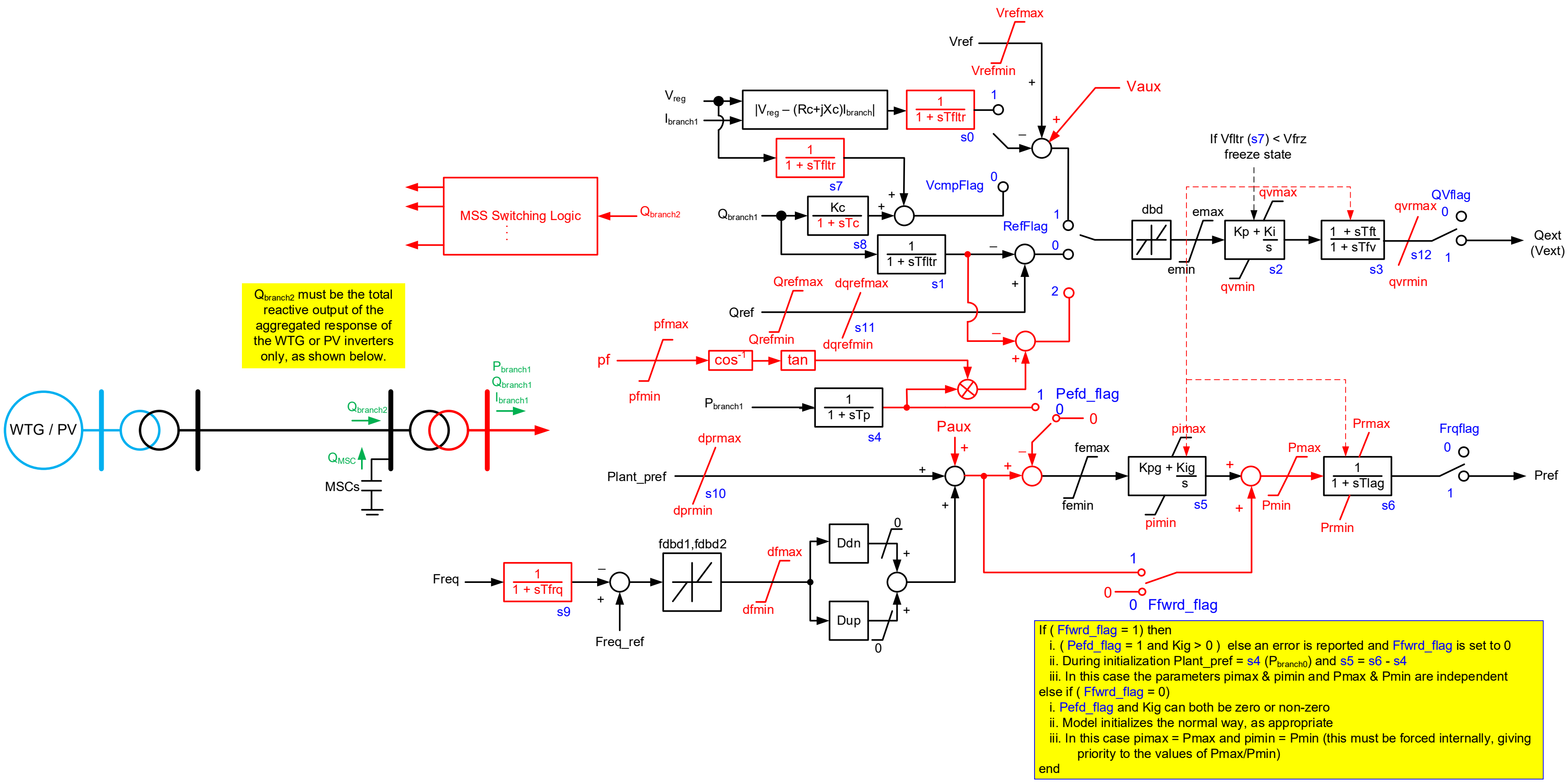


Figure 4-14
The REPC_C power plant controller model. The key difference with REPC_A are shown highlighted in RED.

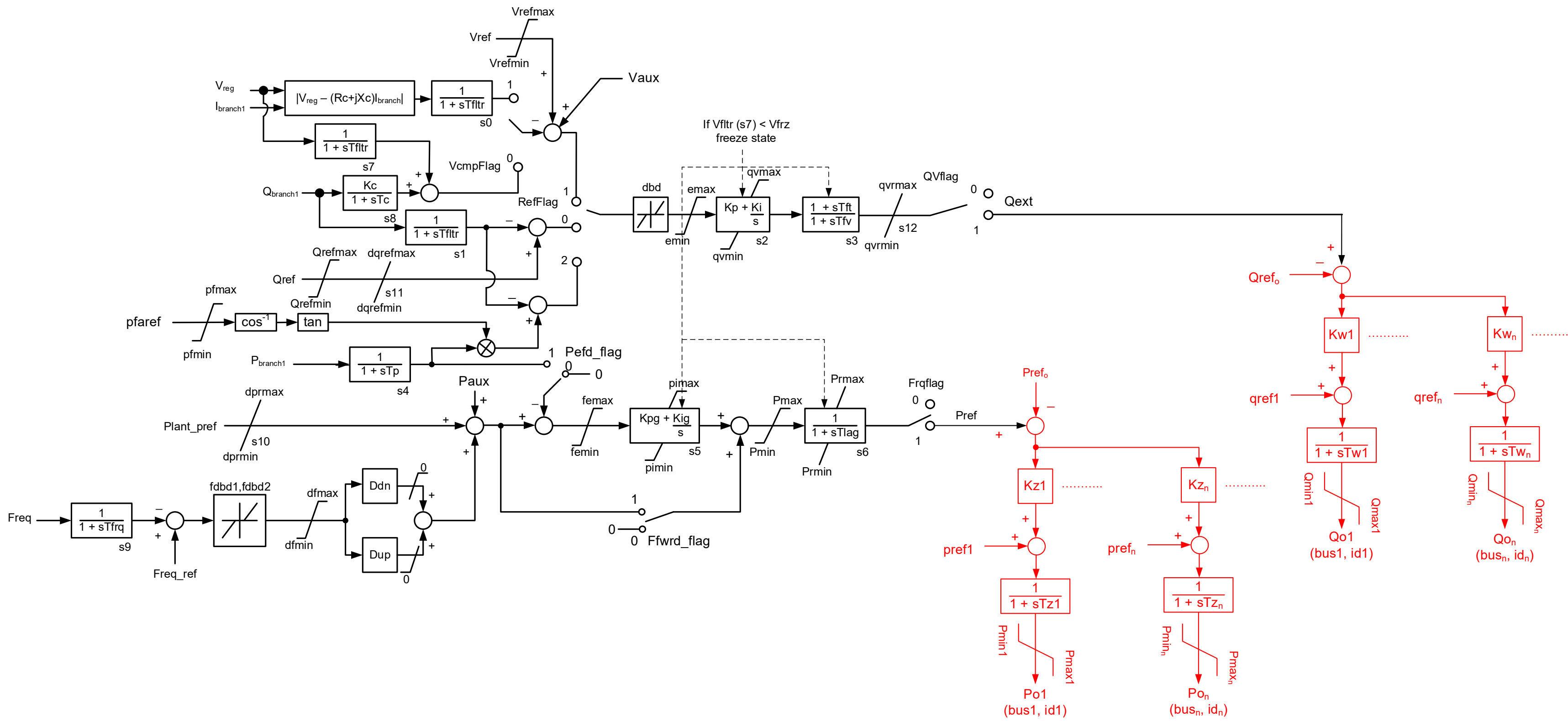


Figure 4-15
The proposed REPC_D hybrid-PPC model.

The Reactive Power Control Path

Figure 4-16 shows the two (2) control paths within the REPC_C model. The top half of the model is associated with the reactive power control path, and is independent of the active power control path. The REPC_A model is similar, with the exception that it does not have a power-factor control path and lacks some of the rate-limits and other limits in the REPC_C model. Now consider the reactive power control part of the PPC in Figure 4-16. There are essentially four (4) options for the control of the reactive power at the point of measurement (POM). The POM is typically the high-voltage side of the substation power transformer of the plant, which is connected to the transmission extra-high voltage (EHV) system. These options are as follows:

1. Voltage control with current compensation (**red path**): By setting *VcmpFlag* = *RefFlag* = 1 the reactive path controls the voltage at the point of measurement (POM) defined in the model (i.e., the regulated bus, which is typically the high-voltage side of the plants substation transformer), with current-compensation. The current-compensation parameters are *Rc* and *Xc*. The voltage regulator is a proportional-integral (PI) controller (*Kp* and *Ki*), with a deadband (*dbd*) and a maximum/minimum error limit (*emax/emin*). The deadband may be set to "0", and the error limits removed (i.e. *emax* = 999 and *emin* = -999).
2. Voltage control with reactive droop (**green path**): By setting *VcmpFlag* = 0 and *RefFlag* = 1 the reactive path controls the voltage at the POM, with reactive droop. The reactive droop is set by *Kc*. The meaning of all other parameters is still as above.
3. Constant-Q Control (**blue path**): By setting *RefFlag* = 0 the reactive path controls the branch Q at the POM. With this setting of *RefFlag*, the value of *VcmpFlag* becomes irrelevant. When this option is selected, the deadband (*dbd*) and error limits (*emax/emin*), if used, are per unit quantities of reactive power (Q) as measured at the POM.
4. Constant power-factor (pf) Control (**magenta path**): This option is available only in REPC_C. By setting *RefFlag* = 2 the reactive path controls the plant's effective power-factor (*pf*) as measured at the POM. With this setting of *RefFlag*, the value of *VcmpFlag* becomes irrelevant. When this option is selected, the deadband (*dbd*) and error limits (*emax/emin*), if used, are per unit quantities of reactive power (Q) as measured at the POM. Note that, if *Pbranch* < 1% of the plant rating and the plant is in pf-control, then upon initialization the software will force the model to constant-Q control (i.e. *RefFlag* is forced from 2 to 0), and a warning message is issued to the user that this has been done since constant power factor control at very low loads does not make sense (e.g., when P = 0 how does one even calculate power factor?).

Some additional notes are pertinent, to outline the differences between REPC_A and REPC_C. Consider Figure 4-13 and Figure 4-14. As explained above, one major difference in the reactive control path is that REPC_C has the option of constant-pf control, while REPC_A does not. The other key differences are: (i) the availability of ramp limits on the Q-reference and the output of the controller, (ii) the availability of reference limits on the Q, pf and voltage references, (iii) the availability of a lag time-constant (to emulating filtering) on the reactive droop (*Tc*), and the repositioning of the voltage measurement filter (*Tfltr*) as it applies to the reactive droop path, (iv) the availability of *QVflag* which allows the user to turn-off the entire reactive control path, and (iv) the availability of automatic shunt-switching. The last control feature is explained in more detail below. Finally, in both models the reactive control path is frozen when the measured voltage at the POM drops below *Vfrz*. There is, however, a significant difference between REPC_A and REPC_C in this regard. For REPC_C there is an additional parameter, *Tfrz*, which determines the time delay during which the PPC is kept in a frozen state after the filtered voltage recovers above *Vfrz*. If *Tfrz* is none-zero the user must ensure that there is proper low-voltage ride-through (LVRT) and voltage control actions at the inverter level controls (i.e. REEC_* + an trip relay models) and that the LVRT controls are properly coordinated with this delay. Moreover, this freezing is applied in REPC_C simultaneously to the active power path as well, and it used the filtered measured POM voltage – states *s7*.

The time constants *Tft* and *Tfv* can be used to represent any intentional phase lead (*Tft*) – typically none – or lag/delay (*Tfv*) in the communication process between the plant controller and the turbines.

<u>AN IMPORTANT NOTE:</u> depending on the settings within the REEC_* model downstream of the plant controller, Qext (the output of the REPC_* model) can be either a "Q-command" or "Voltage-command". Therefore, the values of Qmax/Qmin must be set appropriately to respect the nature of the output signal. For example, if in the downstream REEC_* model Pfflag = 0, Vflag =0 and Qflag = 1 (see Table 4-3) then Qext will be a voltage-set-point and so Qmx/Qmin in the REPC_* model need to be set to values such as 1.1/0.9 (maximum and minimum voltage set-point values). While, if Pfflag = 0, Vflag = 1 or 0, and Qflag = 0 (see Table 4) then Qext will be a Q-reference and so Qmax/Qmin in the REPC_* model need to be set to values such as ± 0.3 (maximum and minimum Q-reference).

REPC_C includes logic for coordinated switching of mechanically switched shunts (MSS), as mentioned above.. This logic was essentially copied from the generic SVS models [20]. For completeness, the switching logic is depicted in Figure 4-17. 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*).

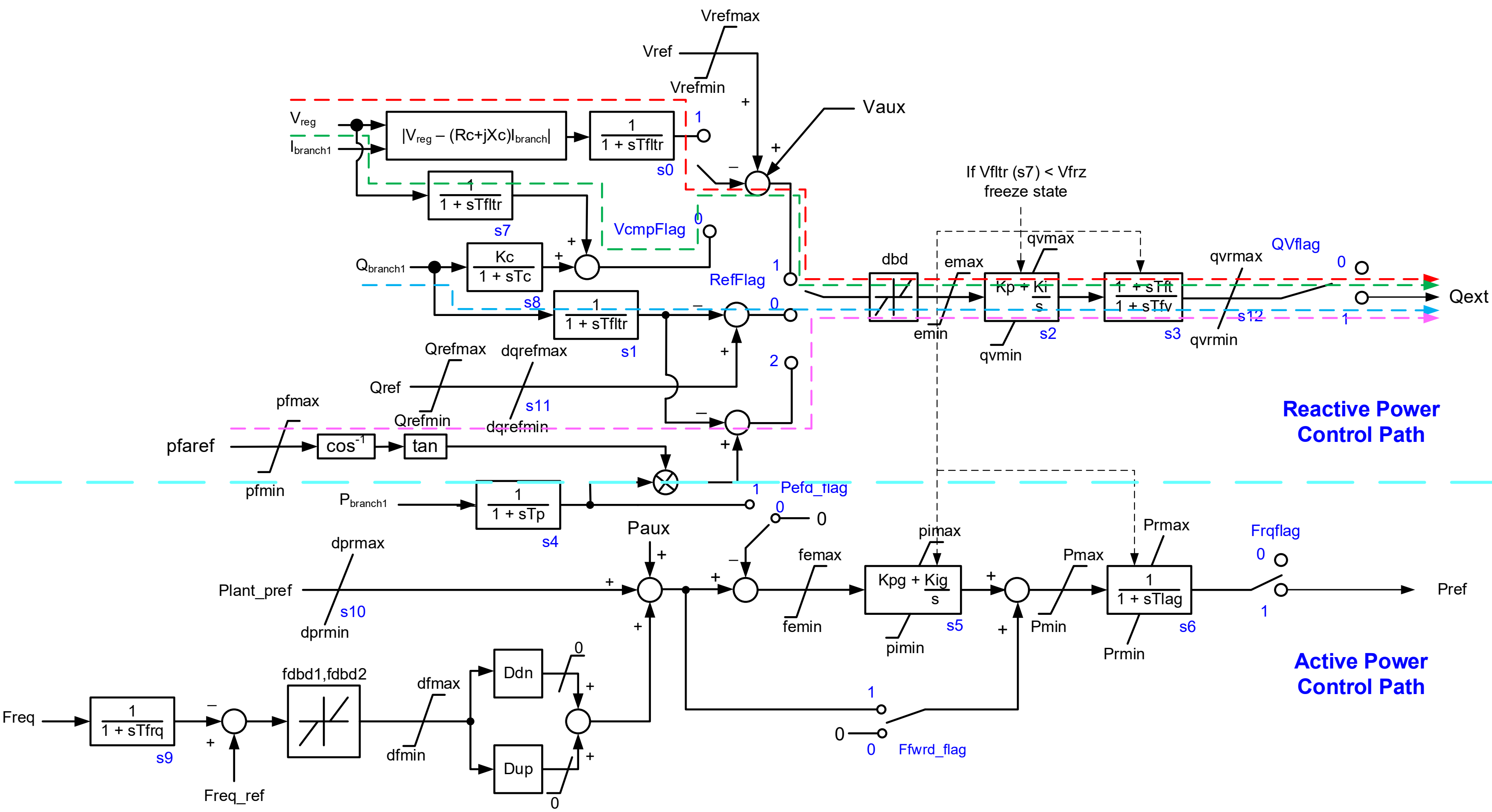


Figure 4-16
The two (2) control paths of the power plant controller model.

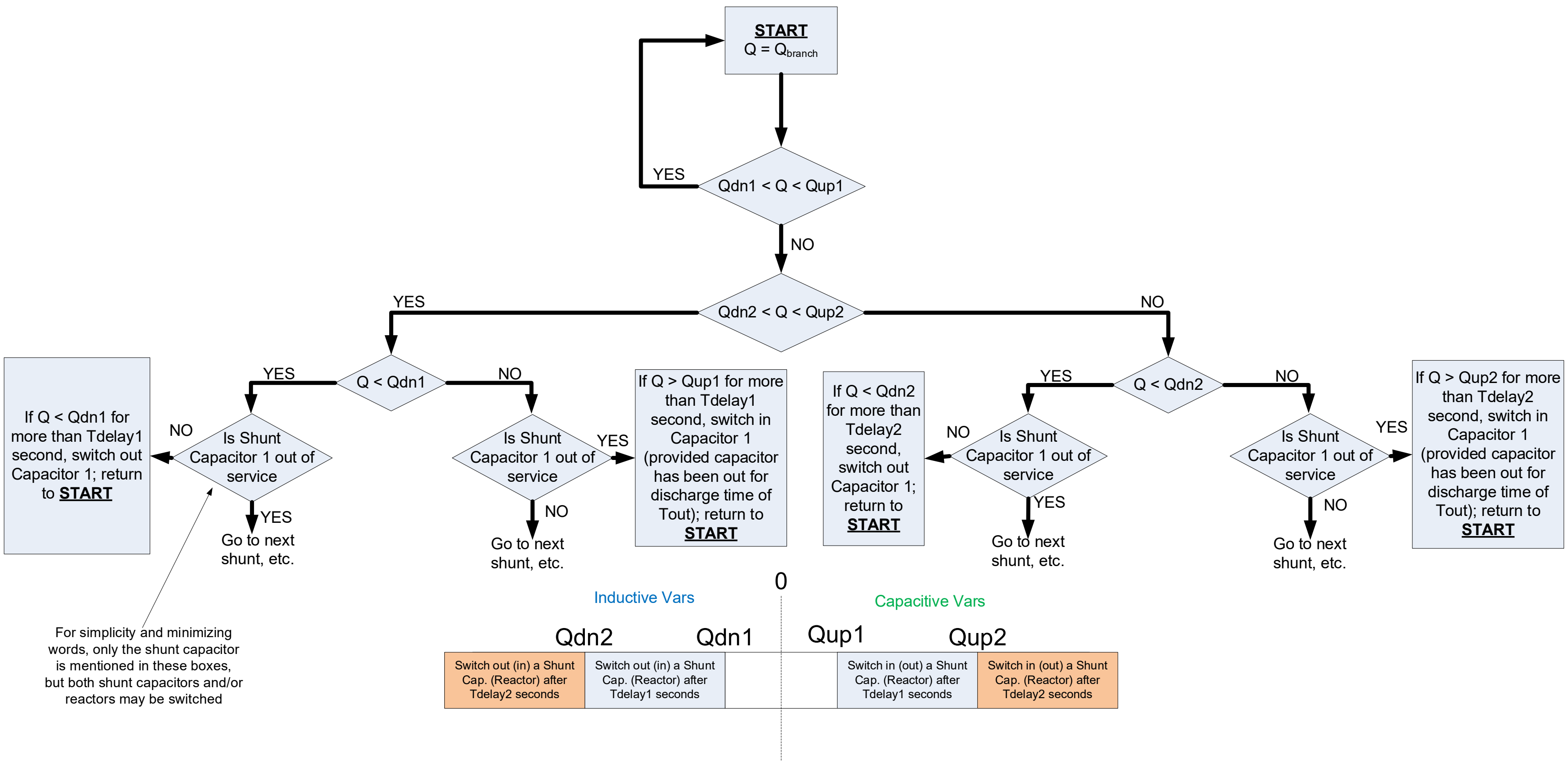


Figure 4-17
Switching logic for the automated switching of MSSs.

The Active Power Control Path

The active power control loop can be used to simulate primary frequency response. Figure 4-18 shows this control path for both REPC_A and REPC_C. Consider first the REPC_A active power control path. This loop can be enabled by setting *Frqflag* = 1, or disabled by setting the flag to 0. The upward (*Dup*) and downward (*Ddn*) regulation droop settings can be different, as well as the deadband on either side (*fdbd1 and fdbd2*). In addition, a plant power reference *Plant_ref* is accessible by the user, which can be used to ramp the plant or controlled by other external models (e.g. AGC). The limits *Pmax/Pmin* and *femax/femin* are simply the power and error limits, respectively.

Now consider the REPC_C model (Figure 4-18). There are three (3) major additions, as compared to REPC_A:

a) There are two (2) additional rate-limits in the plant reference (*dprmax/dprmin*) and the active power command output (*Prmax/Prmin*).

b) The electric power feedback from the POM is optional; that is, by setting *Pefd_flag* to 0 or 1, this feedback may be disabled or enabled, respectively. Great care must be taken in doing this to understand what exactly one is trying to achieve. For example, if *Pefd_flag =1,* then *Kig* must be > 0, for otherwise the controls do not make sense since the error between *Pbranch* and *Plant_ref* would be going through a proportional gain only to develop the total power command, which is infeasible.

c) There is a new feedforward path, which can be engaged or disabled by *Ffwrd_flag*. Again, great care should be exercised when using this path to understand what one is trying to achieved. When *Ffwrd_flag* =1, *Pefd_flag* must also be = 1 *and Kig* must be > 0. Moreover, in this case *pimax/pimin* are different to *Pmax/Pmin* and are typically set to a smaller value such as ± 0.1 pu, since the PI regulator for this case is a vernier controller that simply adjusts the total P command to account for losses on the collector system. When *Ffwrd_flag = 0, pimax/pimin* must be set to the same values as *Pmax/Pmin,* typically 1 and 0 for a generation plant (or 1 and -1 for a BESS).

For the North American commercial tools, the REPC_C model was developed to work with the so-called *baseload flag* that is used by many North American utilities. This flag is set in the power flow data records in many software tools (e.g. GE PSLT™, Siemens PTI PSS®E, etc.). Namely,

- If baseload flag = 0, then the model behaves normally,
- If baseload flag = 1, then *Pmax* = initial power flow MW output of the plant (*Pgeno*) and thus the power order can only go down and not up, and
- If baseload flag = 2, then *Pmax=Pmin = Pgeno* and thus the power order is fixed.

This above point is an extremely important one. This is because in the context of wind and photovoltaic (PV) generation, it needs to be understood that such plants are always operated under their maximum power tracking mode. That is, the plant is always putting out the maximum available incident wind or solar power that is incident on the plant. Thus, no matter the operating point, the plant is not able to provide any upward regulation in the case of an underfrequency event since it is already at its maximum possible power output – this would be modeled by placing the plant in *baseload flag* = 1 condition. However, if the plant has been curtailed by the transmission system operator (e.g. due to transmission network congestion), and thus has room to move up in power, it would then provide frequency response for an underfrequency event under such a scenario, and thus to emulate such a condition *baseload flag* should be set to 0. **Note:** it is important to understand the difference between having primary frequency response (PFR) capability and actually being able to deliver PFR during an underfrequency event. Since many wind and PV plants are typically allowed by a system operator to regularly operate at their maximum power point, it would hence not be possible to extract PFR for underfrequency events from these plants under such an operating mode. This operation mode should, however, not be confused with the absence of the capability to provide PFR, if such control capability has been installed on the equipment. Modern wind and PV plants can certainly have just capability and it has been amply demonstrated in the field [13], [21]. The actual utilization, and delivery of underfrequency PFR from a wind or PV plant will depend on contractual agreements and/or market mechanisms in the region that the plant operates. Such details are outside the scope of this document, but should be understood in the context of proper utilization of the models. Finally, needless to say, when PFR capability is enabled in a plant, it will always be available for over-frequency response (even if under-frequency response is not available), since it is typically always possible to reduce power in any kind of power plant[13].

Finally, the complete parameter list for the REPC model is provided in Table 4-5. Once again it is emphasized that the range of each parameter value, and the suggested typical value of each parameter, as presented in Table 4-5 is simply for the purposes of providing some initial guidance. They are not to be taken as absolute limits on the possible values of the parameters. There may be perfectly legitimate values for the parameters, when the model is properly parameterized for a specific purpose, that are outside of the suggested range of values. Care must always be taken to properly, and meaningfully, parameterize the models, and if modeling an actual project to consult the OEM. Moreover, note that:

- Where a value is stated as “N/A”, this means there is no typical value (e.g. number of the bus in power flow for frequency measurement).
- Where a value is stated as “OEM”, this means that the value should be sought from the original equipment manufacturer and it is not really possible to provide a typical/range of values.
- The power flow bus numbers and ID of the controller switched-shunts is defined differently in various commercial software programs. For example, in GE PSLF™ the switched-shunts are entered in the power flow shunt table and connected back to the REPC_C model through the power flow entries. Conversely, in Siemens PTI PSS®E the bus number and ID of each of the shunts must be entered in the dynamic model. Thus, each specific software manual should be carefully referenced to understand the instantiation of the model and how the shunts, the controlling branch etc. are defined in the specific software tool.

---

[13] There are some limitations to this, as some plants may have a minimum power level under which they will momentarily shutdown the inverters. Thus, when the plant is at its minimum power level, PFR may not be available in either direction, i.e. baseload flag = 2. Again, it is simply important to understand the detailed characteristics of the plant and the operation condition(s) being modeled.

Hybrid-Plants and the REPC_D model

This proposed new plant-controller model REPC_D [22] is based off of the existing REPC_C model, which interfaces to a single aggregated WTG model. The REPC_D model then builds on REPC_C to make it similar to an existing hybrid-controller model REPC_B for controlling multiple aggregated renewable system models downstream. However, REPC_D is a significant improvement from REPC_B and eliminates many of the reported limitations of REPC_B[14]. Thus, REPC_D will have the exact same structure as REPC_C with the only change being the additions shown in **RED** in Figure 4-15, which thus allows the plant controller to control multiple aggregated units. This model is presently under development by several commercial software vendors, and soon to be tested.

[14] https://www.wecc.org/Reliability/Clarification%20on%20Proper%20Use%20of%20REPC%20models.pdf

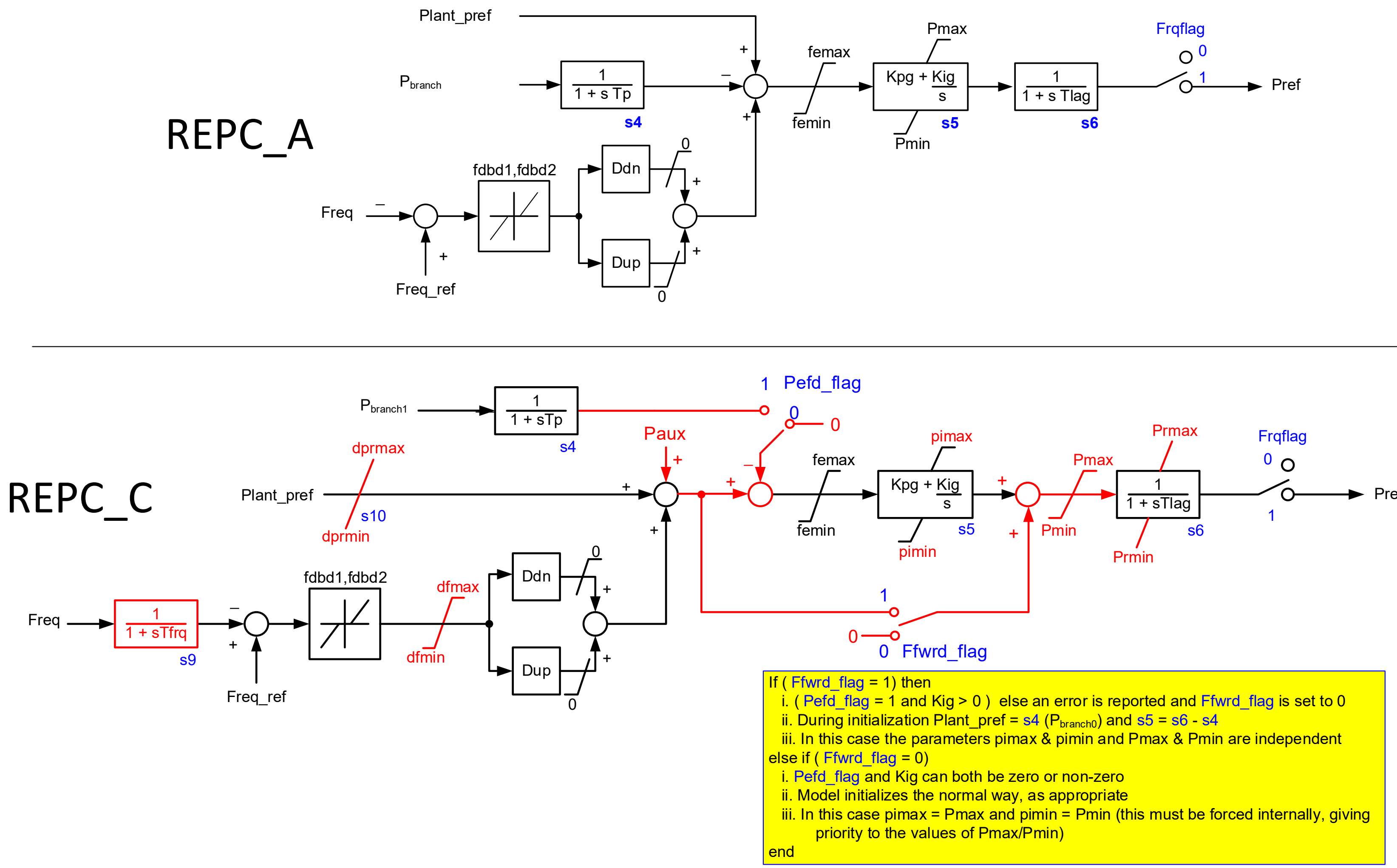


Figure 4-18
The active power control path for REPC_A and REPC_C. The differences are shown in RED.

Table 4-5
Parameters for the REPC_* models

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	REPC_A	REPC_C
1	tfltr	Measurment transducer time constant	0	0.02	0.1	[s]	√	√
2	kp	Proportional gain of reactive power controller	OEM	OEM	OEM	[pu]	√	√
3	ki	Integral gain of reactive power controller	OEM	OEM	OEM	[pu]	√	√
4	tft	Lead time constant	0	0	0.05	[pu]	√	√
5	tfv	Lag time constant	0.05	OEM	0.5	[s]	√	√
6	refflg	0: Reactive power control; 1: Voltage control; 2: Power factor control (only for REPC_C)	0	1	2	flag	√	√
7	vfrz	If $Vfltr < vfrz$, then states freez states s2, s3, s5, and s6; (for REPC_A only s2 is frozen)	0.6	0.7	0.9	[pu]	√	√
8	tfrz	Time delay during which the states are kept frozen after the filtered voltage recovers above $Vfrz$	0.1	0.5	1	[s]		√
9	rc	Current compensation resistance	0	OEM	0.01	[pu]	√	√
10	xc	Current compensation reactance	-0.1	OEM	0.1	[pu]	√	√
11	kc	Reactive droop gain	0	OEM	0.15	[pu/pu]	√	√
12	tc	Time constant associated with reactive power measurement/filtering for the reactive droop function	0.02	0.02	0.5	[s]		√
13	vcmpflg	Flag for selection of 0 - reactrive droop, or 1 - current compensation	0	0	1	flag	√	√
14	emax	Maximum error limit	0.1	999	999	[pu]	√	√
15	emin	Minimum error limit	-999	-999	-0.1	[pu]	√	√
16	dbd	Deadband	0	0	0.01	[pu]	√	√
17	qvmax	Maximum limit of the reactive power (or voltage) for the PI controller	OEM	OEM	OEM	[pu]	√	√
18	qvmin	Minimum limit of the reactive power (or voltage) for the PI controller	OEM	OEM	OEM	[pu]	√	√
19	kpg	Proportional gain for active power control	OEM	OEM	OEM	[pu/pu]	√	√
20	kig	Integral gain for active power control	OEM	OEM	OEM	[pu/pu/s]	√	√
21	tp	Lag time constant on electric power measurement	0.02	0.02	0.5	[s]	√	√
22	fdbd1	Deadband for primary frequency repsonse (PFR) for overfrequency events	-0.01	-0.0006	0	[pu]	√	√
23	fdbd2	Deadband for PFR for underfrequency events	0	0.0006	0.01	[pu]	√	√
24	femax	Maximum error limit	0.01	999	999	[pu]	√	√
25	femin	Minimum error limit	-999	-999	-0.01	[pu]	√	√
26	pimax	Maximum limit of the active power PI controller	1	1	1	[pu]		√
27	pimin	Minimum limit of the active power PI controller	-1	0	0	[pu]		√
28	pmax	Maximum active power limit	1	1	1	[pu]	√	√
29	pmin	Minimum active power limit	-1	0	0	[pu]	√	√
30	prmax	Maximum rate of increase of Pref	OEM	999	999	[pu/s]		√
31	prmin	Maximum rate of decrease of Pref	-999	-999	OEM	[pu/s]		√
32	dprmax	Maximum rate of increase of plant Pref	OEM	999	999	[pu/s]		√
33	dprmin	Maximum rate of decrease of plant Pref	-999	-999	OEM	[pu/s]		√
34	tlag	Lag time constant	0.05	OEM	0.5	[s]	√	√

Table 4-5 (continued): Parameter list for the REPC_* models

35	ddn	Downside droop for PFR (i.e., for an overfreqeuncy event to push power donw)	0	20	OEM	[pu/up]	√	√
36	dup	Upside droop for PFR (i.e., for an underfrequency event to push power up)	0	20	OEM	[pu/up]	√	√
37	frqflg	Flag to 1 - turn on the PFR functionality, or 0 - to turn it off	0	1	1	flag	√	√
39	vrefmax	Maximum limit on Vref	1.05	1.1	1.1	[pu]		√
40	vrefmin	Minimum limit on Vref	0.9	0.9	0.95	[pu]		√
41	qrefmax	Maximum limit on Qref	OEM	999	999	[pu]		√
42	qrefmin	Minimum limit on Qref	-999	-999	OEM	[pu]		√
43	dqrefmax	Maximum rate of increase of Q reference	OEM	999	999	[pu/s]		√
44	dqrefmin	Maximum rate of decrease of Q reference	-999	-999	OEM	[pu/s]		√
45	qvrmax	Maximum rate of increase of Qext	OEM	999	999	[pu/s]		√
46	qvrmin	Maximum rate of decrease of Qext	-999	-999	OEM	[pu/s]		√
47	pfmax	Maximum limit on power factor	0.95	0.95	0.8	N/A		√
48	pfmin	Minimum limit on power factor	-0.8	-0.95	-0.95	N/A		√
49	MSSflag	If MSSflag = 1, then the MSS switching logic is activated, else it is deactivated	0	0	1	flag		√
50	MSSbus1	MSSbus1 and MSSbus2 define the branch where Qbranch2 is measured for controlling the MSS switching	N/A	N/A	N/A	bus no.		√
51	MSSbus2		N/A	N/A	N/A	bus no.		√
52	Qdn1	First stage of capacitor (reactor) switching out (in) (Qdn1 < 0)	N/A	N/A	N/A	[pu]		√
53	Qdn2	Second stage of capacitor (reactor) switching out (in) (Qdn2 < Qdn1)	N/A	N/A	N/A	[pu]		√
54	Qup1	First stage of capacitor (reactor) switching in (in) (Qup1 > 0)	N/A	N/A	N/A	[pu]		√
55	Qup2	First stage of capacitor (reactor) switching in (in) (Qup2 > Qup1)	N/A	N/A	N/A	[pu]		√
56	Tdelay1	Time delay after which a a capacitor (reactor) is switched out (in) if Q < Qdn1 (or cap. in or reactor out if Q > Qup1)	N/A	N/A	N/A	[s]		√
57	Tdelay2	Time delay after which a capacitor (reactor) is switched out (in) if Q < Qdn2 (or Q > Qup2) – typically Tdelay2 < Tdelay1.	N/A	N/A	N/A	[s]		√
58	Tmssbrk	Time it takes to switch in (out) a mechanically switched shunt - essentially the time delay associated with the breaker	N/A	N/A	N/A	[s]		√
59	Tout	Discharging time of a capacitor that has just been switched out; the capacitor cannot be switched back in until Tout	N/A	N/A	N/A	[s]		√
60	tfrq	Frequency transducer/filter time constant	0.02	0.1	0.25	[s]		√
61	Ffwrd_flag	Enable (1) or disable (0) feedforward path	0	OEM	1	flag		√
62	Pefd_flag	Enable (1) or disable (0) electrical power feedback	0	OEM	1	flag		√
63	vfreq	If the voltage at the bus where frequency is monitored < *vfreq* then measured frequency is set to 1 p.u.	0.5	0.8	0.8	[pu]		√
64	QVflg	Flag: 0 – disable volt/var control completely, or 1 – enable volt/var control.	0	1	1	[pu]		√
65	dfmax	Maximum limit on frequency deviation	0.01	999	999	[pu]		√
66	dfmin	Minimum limit on frequency deviation	-999	-999	-0.01	[pu]		√
67	fbus	Bus at which frequency is monitored (if set to zero then from bus of monitored branch used)	N/A	N/A	N/A	bus no.	√	√
68	From Bus	From bus of the monitored branch at the point of measurement (POM) of the plant (also bus where voltage/Q is controlled)	N/A	N/A	N/A	bus no.	√	√
69	To Bus	To bus of the monitored branch at the point of measurement (POM) of the plant	N/A	N/A	N/A	bus no.	√	√
70	Branch ID	ID of the monitored branch at the point of measurement (POM) of the plant	N/A	N/A	N/A	ID	√	√

Note 1: where a parameter range is designated by "OEM" is meant that there is no typical value or range that can be truly given. In the end, for any actual proposed or built project the value of all the parameters should come from the OEM, parameterized to the extent possible to match the actual equipment. However, here some typical, and range of values, have been provided simply for guidance. The range of values are not to be interpreted as absolute limits on the values of parameters.

Note 2: User should carefully review and set the "baseload" flag for the associated plant, typically in the power flow record of the software platform. See discussion on baseload flag on page 4-31.

4.4 Wind Turbine Generator Mechanical Side Models and Other Auxiliary Models

As will be summarized briefly in the next section, a PV plant and a BESS plant can be modeled for positive-sequence stability analysis using a combination of REGC_*, REEC_* and REPC_* models. That is, for a type 4 wind power plant (WPP), research has shown that all that is needed to be modeled is an appropriate combination of the same three models [3]. In some cases, where a type 4 WPP exhibits torsional oscillations in the response of its electrical power following a close in fault, this can be emulated with a simple shaft-dynamics emulation model (WTGT_B) [5]. However, for a type 3 WPP the typical industry approach is to model all the mechanical components, namely, the pitch-controller, the torque-controller, the aero-dynamics and the shaft-dynamics. Thus, in this section a brief summary of all these mechanical models used for type 3 WPPs is given. Moreover, WPPs also have some auxiliary controls that should also be modeled when used. These models are also discussed here. Thus, everything discussed in this section pertains only to WPPs.

The Aero-Dynamic Model

The aero-dynamic model is used only for a type 3 WTG. It takes on a simple form, and is based on the simple model developed in [23]. The WTGA_A model, as shown in Figure 4-19, only has two (2) parameters. They are:

- *Ka* – the aero-dynamic gain factor, which is typically set to 0.007 [23], unless otherwise specified by the OEM.
- θo – the initial blade pitch angle in degrees. If the plant is being modeled as running at its maximum available power point, then θo should be set to 0. If, however, the plant is being modeled as curtailed (e.g., to emulate the availability of headroom to simulate an underfrequency event) then θo should be set to some value between 5 to 10 degrees.

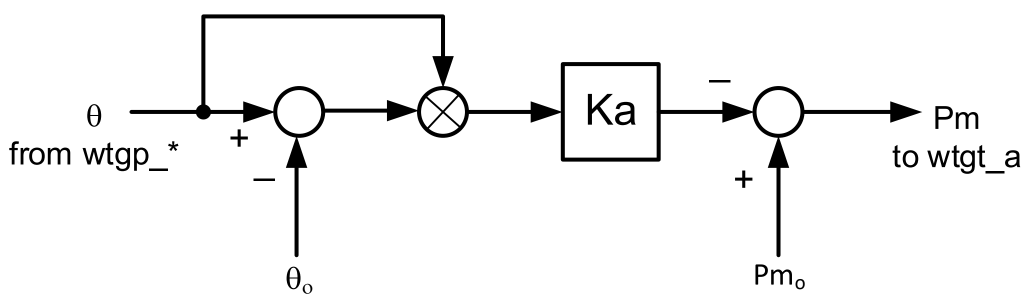


Figure 4-19
The WTGA_A aero-dynamic model based on [21].

The Drive-Train Shaft Dynamics

There are presently two drive-train shaft dynamics models:

- WTGT_A – this model was originally developed and first released around 2014 in commercial tools [1]. It is a simple two-mass equivalent model of the drive train, as shown in Figure 4-20. This model should truly only be used with type 3 WTGs.
- WTGT_B – this model was developed in 2018 [9] and first released around 2019/2020 in commercial tools. It is also a simple two-mass equivalent model of the drive train, as shown

in Figure 4-21. This model should truly only be used with type 4 WTGs. The difference between WTGT_B and WTGT_A is shown in RED in Figure 4-21. The difference is the addition of a lag block between electrical power (*Pe*) and mechanical power (*Pm*). When a type 4 WTG is modeled, all the mechanical side models are neglected (i.e. pitch control, torque control, etc.). Now for a type 4 WTG, where one might wish to model the torsional ripple in the electrical power response following a fault, the shaft dynamic model can be introduced. However, if the WTGT_A model is used then *Pm* remains constant. This results in a net increase in speed after the simulation of a fault or other disturbance that momentarily decreased *Pe*, and thus a slight error in *Pe* in steady-state once the fault clears. In the actual equipment, following a disturbance, the change in turbine speed initiates the pitch control to adjust *Pm* to bring the turbine back to its original steady-state speed and power. Thus, by introducing the lag time constant *Tp* in the WTGT_B, *Pm* changes in a way that is similar (certainly not exactly the same) to the action of the pitch control following a disturbance in *Pe*, in a simple way without having to model the details of the pitch-controller etc. Thus, the steady-state error in *Pe* does not occur. This is illustrated by a simple example simulation in Figure 4-22.

The full parameter list for the WTGT_* models is given in Table 4-6. Again, note that the range of each parameter value, and the suggested typical value of each parameter, as presented in the table are simply for the purposes of providing some <u>initial</u> guidance. Care must always be taken to properly, and meaningfully, parameterize the models, and if modeling an actual project to consult the OEM.

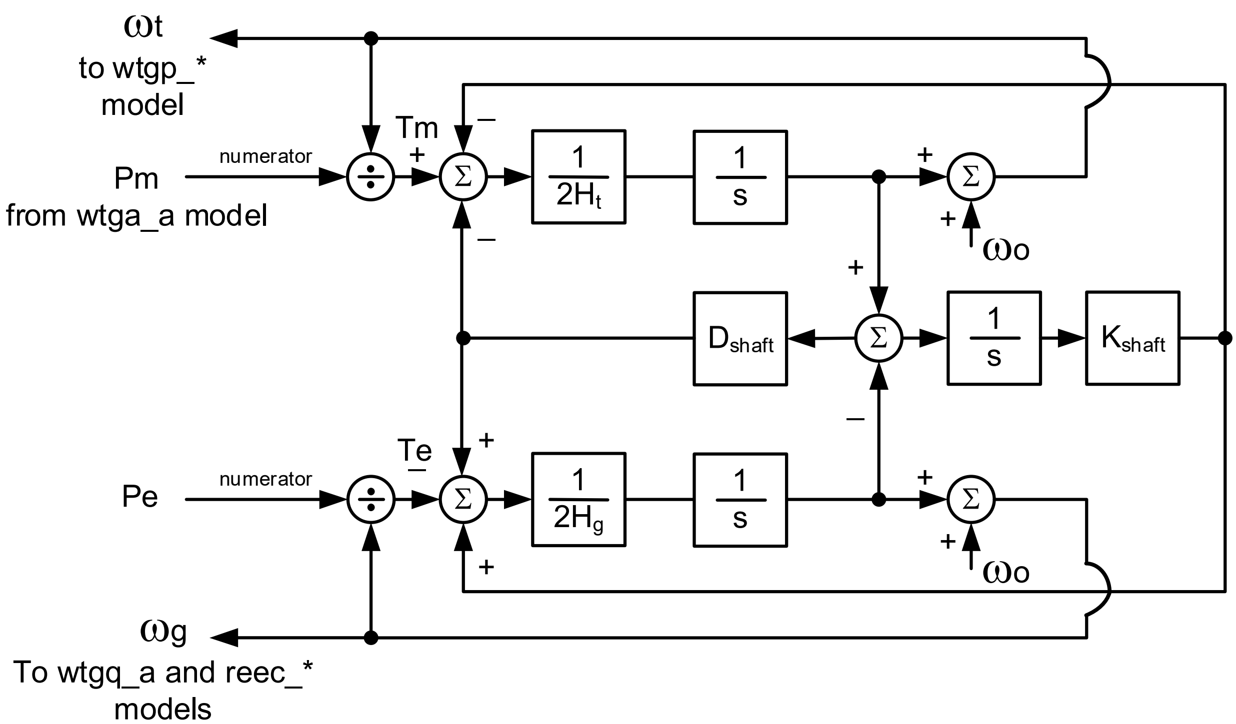


Figure 4-20
The WTGT_A model – to be used with type 3 WTGs only.

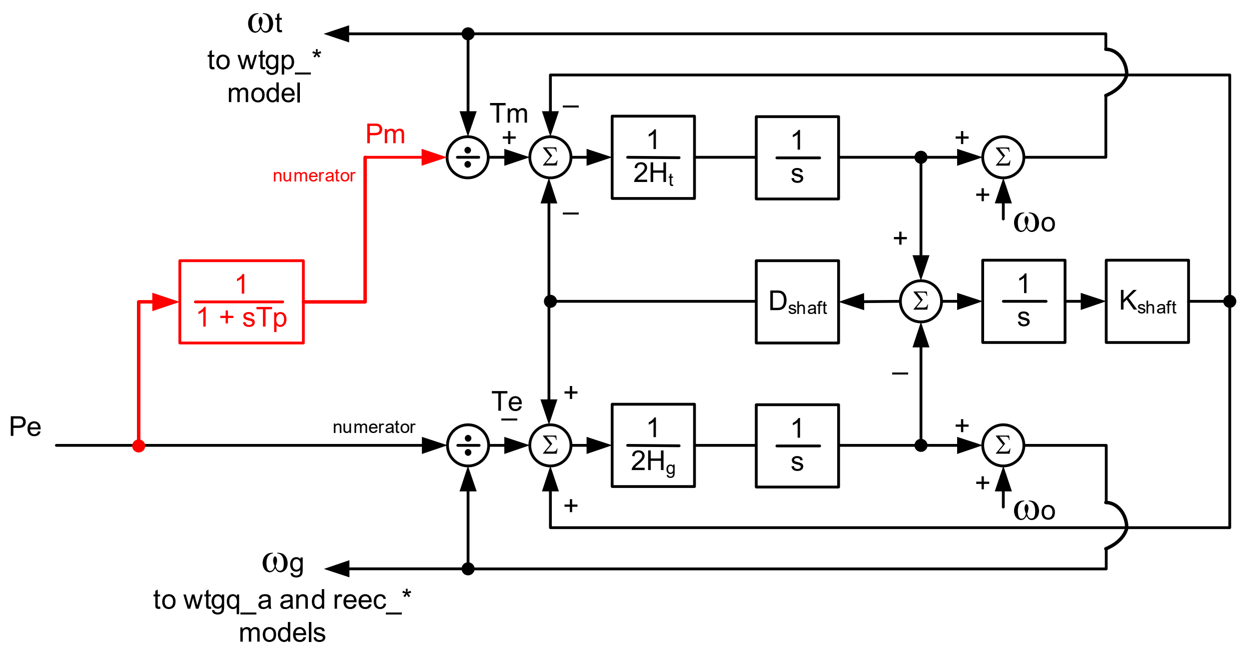


Figure 4-21
The WTGT_B model – to be used with type 4 WTGs only.

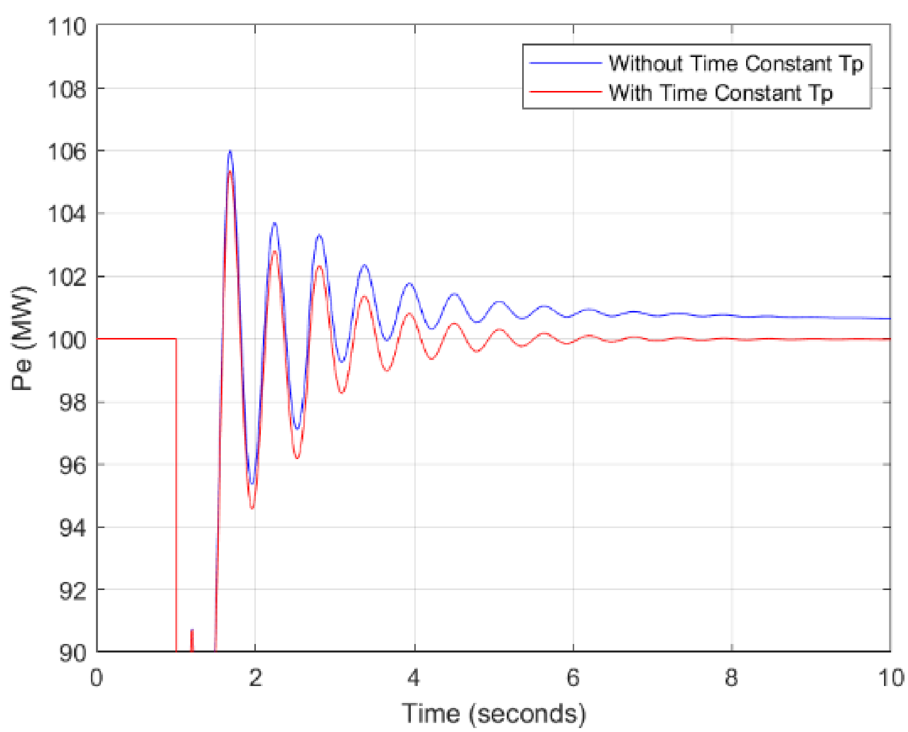


Figure 4-22
The simulation of a nearby fault, for a type 4 WTG using the WTGT_A model (without *Tp*) and the WTGT_B model (with *Tp*).

Table 4-6
Parameter list for the WTGT_* models.

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	WTGT_A	WTGT_B
1	ht	Turbine inertia	OEM	OEM	OEM	[MWs/MVA]	√	√
2	hg	Generator inertia	OEM	OEM	OEM	[MWs/MVA]	√	√
3	dshaft	Damping coefficient	OEM	OEM	OEM	[pu]	√	√
3	kshaft	Stiffness constant	OEM	OEM	OEM	[pu]	√	√
4	wo	Initial shaft speed	1	1	1.3	[pu]	√	√
5	Tp	Time constant	0.1	0.5	1	[s]		√

The Pitch-Controller

The pitch controller model is used only for type 3 WTGs. There are presently two (2) such models:

- WTGP_A – this model was originally developed and first released around 2014 in commercial tools [1].
- WTGP_B – this model was developed in 2018 [9] and first released around 2019/2020 in commercial tools. It is an enhancement of WTGP_A, in order to provide a little more flexibility with the controller limits.

The models are shown in Figure 4-23 and Figure 4-24, respectively. The difference between the two models is shown in **RED** in Figure 4-24. As can be seen the only difference is the fact that the three (3) controller limits were changed to make the model more flexible. The non-windup limits are, however, tied together to ensure none of the limits windup (see [9] for the details).

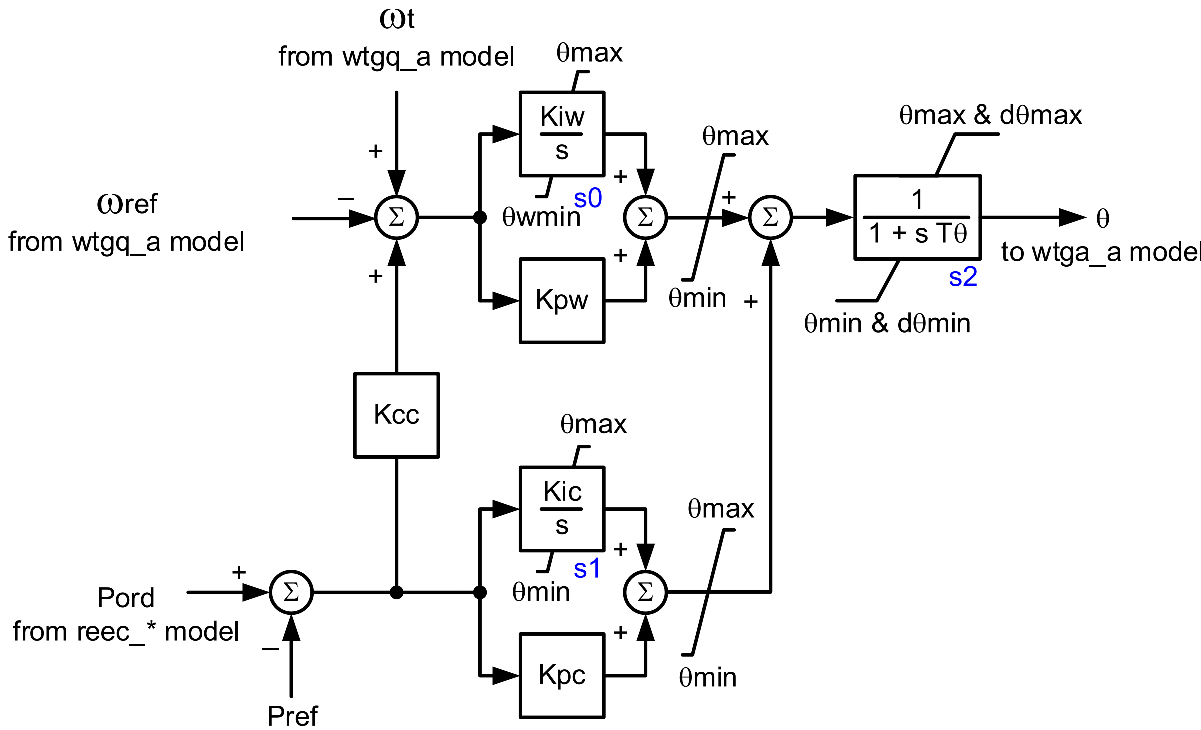


Figure 4-23
The WTGP_A model

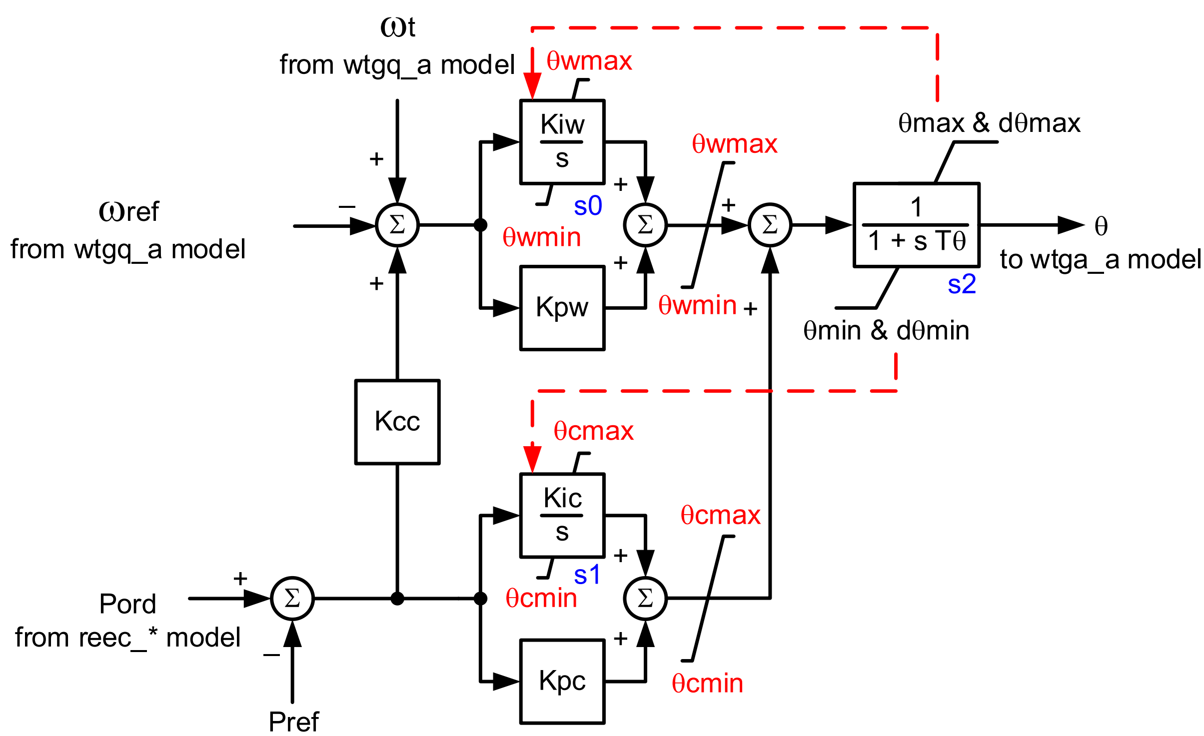


Figure 4-24
The WTGP_B model

The full parameter list for the WTGP_* models is given in Table 4-7. Again, note that the range of each parameter value, and the suggested typical value of each parameter are simply for the purposes of providing some <u>initial</u> guidance. Care must always be taken to properly, and meaningfully, parameterize the models, and if modeling an actual project to consult the OEM.

Table 4-7
Parameter list for the WTGP_* models

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units	WTGP_A	WTGP_B
1	kiw	Pitch controller integral gain	OEM	OEM	OEM	[pu/pu/s]	√	√
2	kpw	Pitch controller proportional gain	OEM	OEM	OEM	[pu/pu]	√	√
3	kic	Pitch compensation integral gain	OEM	OEM	OEM	[pu/pu/s]	√	√
4	kpc	Pitch compensation proportional gain	OEM	OEM	OEM	[pu/pu]	√	√
5	kcc	Proportional cross-compensation gain	0	0	OEM	[pu/pu]	√	√
6	tθ	Pitch time constant	0.2	0.3	0.5	[s]	√	√
7	θmax	Maximum pitch angle limit	25	OEM	50	[deg]	√	√
8	θmin	Minimum pitch angle limit	-5	OEM	0	[deg]	√	√
9	θrmax	Maximum pitch angle rate limit	5	OEM	15	[deg/s]	√	√
10	θrmin	Minimum pitch angle rate limit	-15	OEM	-5	[deg/s]	√	√
11	θwmax	Maximum pitch PI controller limit	25	OEM	50	[deg]		√
12	θwmin	Minimum pitch PI controller limit	-5	OEM	0	[deg]		√
13	θcmax	Maximum pitch compensation PI controller limit	25	OEM	50	[deg]		√
14	θcmin	Minimum pitch compensation PI controller limit	-5	OEM	0	[deg]		√

The Torque-Controller

There is presently a single torque-controller model, WTGQ_A, used for modeling type 3 WTGs and originally developed and first released around 2014 in commercial tools [1]. The model is shown in Figure 4-25. Table 4-8 provides the models parameter list. It is a simplified generic model. The model is relatively simple. It takes in the speed of the generator (ω_g), the electrical power developed by the generator (*Pe*), and the power reference coming from the power plant controller ($Pref_o$), and thus determines the electrical-torque needed. The function *f(Pe)* is a piecewise linear function defined by the four pairs that are parameters 6 through 13 in Table 4-8. This function defines the variable speed reference at a given power output, and should be defined by the OEM. The flag, Tflag, allows the user to determine whether the toque is changed based on the speed reference and change in generator speed, or the power reference. Again, the OEM should advise on the choice of the flag setting.

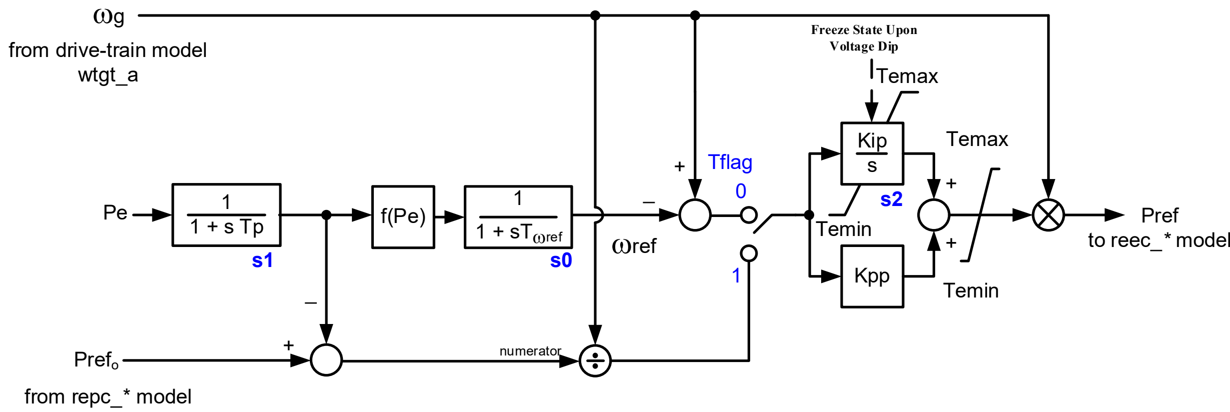


Figure 4-25
The WTGQ_A model

Table 4-8
Parameter list for the WTGQ_A model

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units
1	kip	Integral gain	OEM	OEM	OEM	[pu/pu/s]
2	kpp	Proportional gain	OEM	OEM	OEM	[pu/pu]
3	tp	Power measurement lag time constant	0.02	0.05	1	[s]
3	twref	Speed reference time constant	5	60	60	[s]
4	temax	Maximum torque	0.9	1	1.2	[pu]
5	temin	Minimum torque	0	0.05	0.1	[pu]
6	p1	1st power point	OEM	OEM	OEM	[pu]
7	spd1	1st speed point	OEM	OEM	OEM	[pu]
8	p2	2nd power point	OEM	OEM	OEM	[pu]
9	spd2	2nd speed point	OEM	OEM	OEM	[pu]
10	p3	3rd power point	OEM	OEM	OEM	[pu]
11	spd3	3rd speed point	OEM	OEM	OEM	[pu]
12	p4	4th power point	OEM	OEM	OEM	[pu]
13	spd4	4th speed point	OEM	OEM	OEM	[pu]
14	tflag	Flag to specify PI controller input	0	OEM	1	flag

The Weak-Grid Option Model

Some vendors have indicated that in some cases they offer a supplemental controller called a weak grid option (WGO) [9]. Thus, recently a simple generic model, WTGWGO_A, was developed [9] to emulate this function. It is an auxiliary controller. The model is shown in Figure 4-26. This auxiliary control would fit between the plant controller (REPC_*) and the electrical controller 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. Presently, this model has been developed to be used only for type 4 WTGs – i.e. between

REPC_* and REEC_*, as shown below. Moreover, the major vendor that offers this supplemental controller, does so on their type 4 technology.

This is a rather specialized supplemental controller, that is used by the OEM if and when needed for a given WPP application, when the WPP is being installed in a known weak region of the bulk power system. Thus, this model should only be used when needed and with OEM provided parameters. That said, the model's parameter list is provided in Table 4-9.

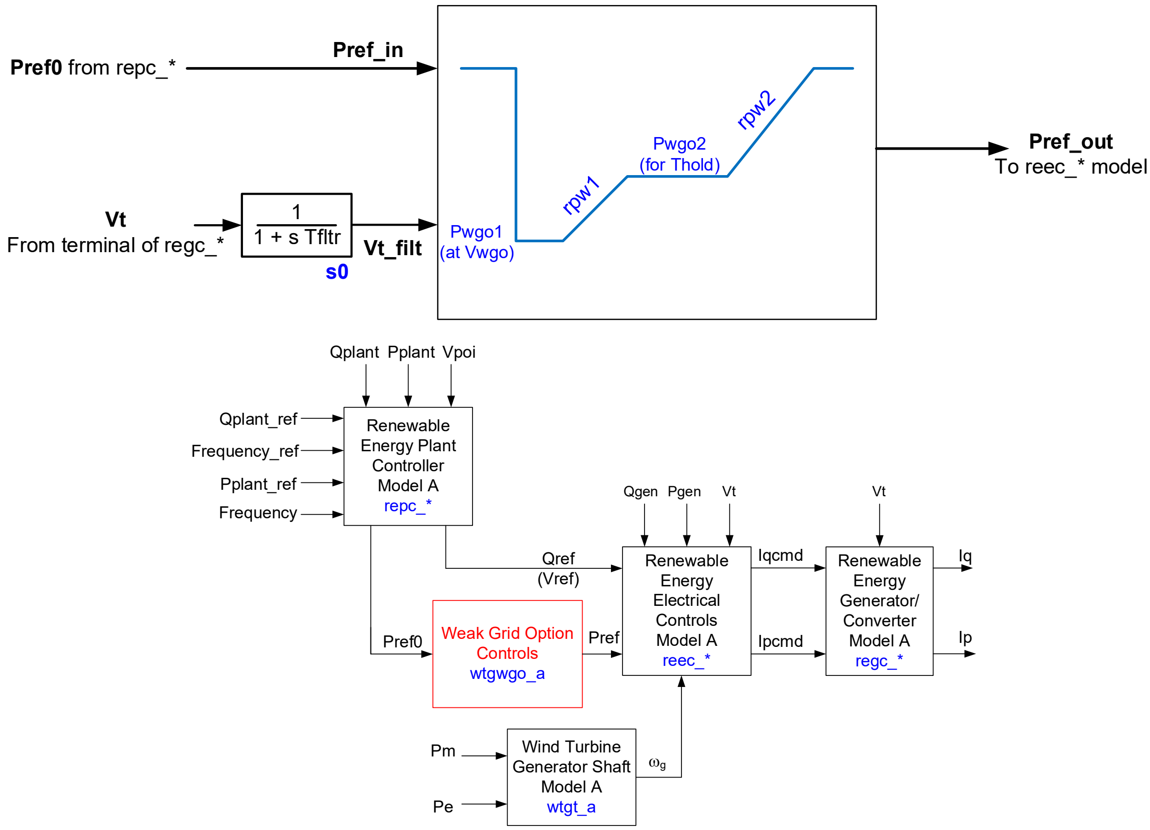


Figure 4-26
The WTGWGO_A model

Table 4-9
Parameter list for WTGWGO_A model

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units
1	tfltr	Filter time constant, sec	0.02	0.02	0.05	[s]
2	vwgo	Voltage below which the WGO function is initiated	OEM	OEM	OEM	[pu]
3	pwgo1	Power reference held during a voltage dip when WGO is initiated	OEM	OEM	OEM	[pu]
3	rpw1	Ramp rate at which power is increased from *pwgo1* to *pwgo2*	OEM	OEM	OEM	[pu/s]
4	pwgo2	Power reference held for *thold* seconds after a voltage dip	OEM	OEM	OEM	[pu]
5	rpw2	Ramp rate at which power is increased from *pwgo2* back to normal	OEM	OEM	OEM	[pu/s]
6	thold	Time for which the power reference is held at *pwgo2*	OEM	OEM	OEM	[s]
7	eps	Small hysteresis on voltage recovery to start the first ramp	0.01	0.01	0.02	[pu]

The Inertia-Based Fast Frequency Response Model

Another auxiliary controller that was recently developed [9], is the so-called inertia-based fast-frequency response (IBFFR) controls for WTGs. The model is to be used only with type 3 and 4 WTGs. It is outside of the scope of this document to describe this functionality and its many aspects and nuances. For a more detailed description the reader should consult [9], [24], [25], and other similar references. This control feature, which is an additional functionality offered by all major WTG OEMs, is an auxiliary controller that temporarily draws on the stored kinetic energy in the rotating shaft of the WTG, and injects some of this energy into the grid to provide a burst of power at the onset of a large under-frequency event to help restrain the rate of change of system frequency. Thus, it is an emulation of the so-called "inertial-response" of a conventional synchronous generator. There are, however, many differences. Briefly, 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) incident on the 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 presented here, or detailed user-written vendor specific model, one thing is for certain and that is one 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 (see Figure 3-1 and Figure 3-2). 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 (see e.g., [26]). 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. This is the underlying assumption behind this model.

The IBFFR model behaves as shown diagrammatically in Figure 4-27. That is, the action of the IBFFR is characterized by four (4) regions, as shown in the figure, 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 when an IBFFR response is invoked by a large frequency deviation.
- *Tpeak* – which is the time (duration) that the WTG remains at the peak value of the IBFFR response, 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. This is not a user input, but it is calculated as discussed below.

These parameters thus define the dynamic behavior of the IBFFR, in addition to one other parameter, the frequency deadband (*dbd*). When the frequency, as measured at the WTG or wind power plant POM, falls below (1 – *dbd*) [pu] then the IBFFR function is initiated. Again, it is emphasize that IBFFR acts only for under-frequency events. This is how the function is also implemented in actual equipment presently. Thus, the model is shown in Figure 4-28.

The model may be explained as follows:

- The error in frequency is calculated (*err*) where frequency is measured at the POM of the wind power plant . 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 $s0 \geq dP.Po$ then $out = 1$, else out = 0. Then $out2 = out$ (the output of *F2*) after a delay of *Tpeak* seconds. Where *Po* here (and in all cases below) denotes the initial turbine electrical power output as determined from the initial power flow solution.
- The function *F3* represents the following simple logic: if $s1 \leq -(dP + dPmin).Po$ then $out3 = 1$, else $out3 = 0$.
- The recovery time (*Trec*). The parameter should typically be set to 0. When set to 0 by the user, the model internally calculates the recovery time in order to ensure that the energy taken out of the shaft (Area A in Figure 4-27) is equal to the energy returned to the shaft (Area B in Figure 4-27), which gives:

$$Trec = \frac{2dP}{dPmin}\left[\frac{Trise}{2} + Tpeak + \left(\frac{dP}{dP + dPmin}\right)\frac{Tfall}{2}\right] - Tfall\left[1 - \frac{dP}{dP + dPmin}\right] \quad (1)$$

Thus, the model is characterized by six (6) sets of values of *dP*, *dPmin*, *Trise*, *Tpeak, Tfall* and *Trec* associated with six different power levels of the turbine (*p1* to *p6*). As discussed briefly above, the actual amount of IBFFR available from each WTG is dependent of the incident wind energy (wind speed) and the rotation speed of the shaft of the WTG. 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, the assumption is made that all the WTGs within the single aggregated WTG model are all at the same wind speed and output power, and that the initial power output of the WTG (in per unit of the rated output as determined from the initial power flow solution) is a reasonable indicator of both these variables (i.e. incident wind speed and rotor speed). Thus, this matrix of 6 × 6 values works in the following way:

```
if (Po ≥ p6)
        dP = dP6
        dPmin = dPmin6
        Trise = Trise6
        Tpeak = Tpeak6
        Tfall = Tfall6
elseif (Po ≥ p5)
        dP = dP5
        dPmin = dPmin5
        Trise = Trise5
        Tpeak = Tpeak5
        Tfall = Tfall5
elseif (Po ≥ p4)
        dP = dP4
        dPmin = dPmin4
```

Trise = Trise4
Tpeak = Tpeak4
Tfall = Tfall4
elseif (Po ≥ p3)
dP = dP3
dPmin = dPmin3
Trise = Trise3
Tpeak = Tpeak3
Tfall = Tfall3
elseif (Po ≥ p2)
dP = dP2
dPmin = dPmin2
Trise = Trise2
Tpeak = Tpeak2
Tfall = Tfall2
elseif (Po ≥ p1)
dP = dP1
dPmin = dPmin1
Trise = Trise1
Tpeak = Tpeak1
Tfall = Tfall1
else
Model is inactive – that is there is no IBFFR available
end

Note that the *Po* is the value of the initial steady-state power output of the "aggregated" wind turbine generator just prior to the initialization that comes from the power flow solution. Thereafter, once an IBFFR event starts, the value of Po is unchanged.

Note: the IBFFR model should be used only in frequency stability studies. This simple model may not behave well if used when performing simulations of transmission faults close to the terminals of the WTG[15].

Once the IBFFR function is initiated, at the beginning of an under-frequency event, it must run its full course and the recovery period be completed. Depending on the value of the *Tlapse* parameter, the next time that the IBFFR function is made available will be *Tlapse* seconds after the full completion of the first instance of IBFFR. Typically, *Tlapse* is of the order of many minutes and much care should be exercised by the user not to enter an unrealistic value here. If a number is entered by the user for *Tlapse* that is ≤ 0, then the software will internally set *Tlapse* = infinity, that is IBFFR is exercised once and once only during the entire simulation.

Finally, note that the six (6) *Trec* values in the model should typically be set to zero (0). By doing, as stated above, the model internally calculates the value of *Trec* per equation (1). If, however, the user wishes to defined a *Trec* that is greater than the calculated value using

---

[15] See https://www.wecc.org/Reliability/WECC_White_Paper_Frequency_062618_Clean_Final.pdf which is the WECC white paper on frequency calculation at or near faulted buses; such issues could falsely initiate an IBFFR event, thus this model should be used with caution when studying a combination of faults and frequency events.

equation (1), for each of the designated six operation points, then the user may populate the *Trec* parameters. In practice, Area B (in Figure 4-27) is actually larger than Area A in many 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 *Trec* 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.

The complete parameter list is provided in Table 4-10, again with the reminder that all values shown are for guidance only and the greatest care must be taken when parameterizing, in consultation with an OEM.

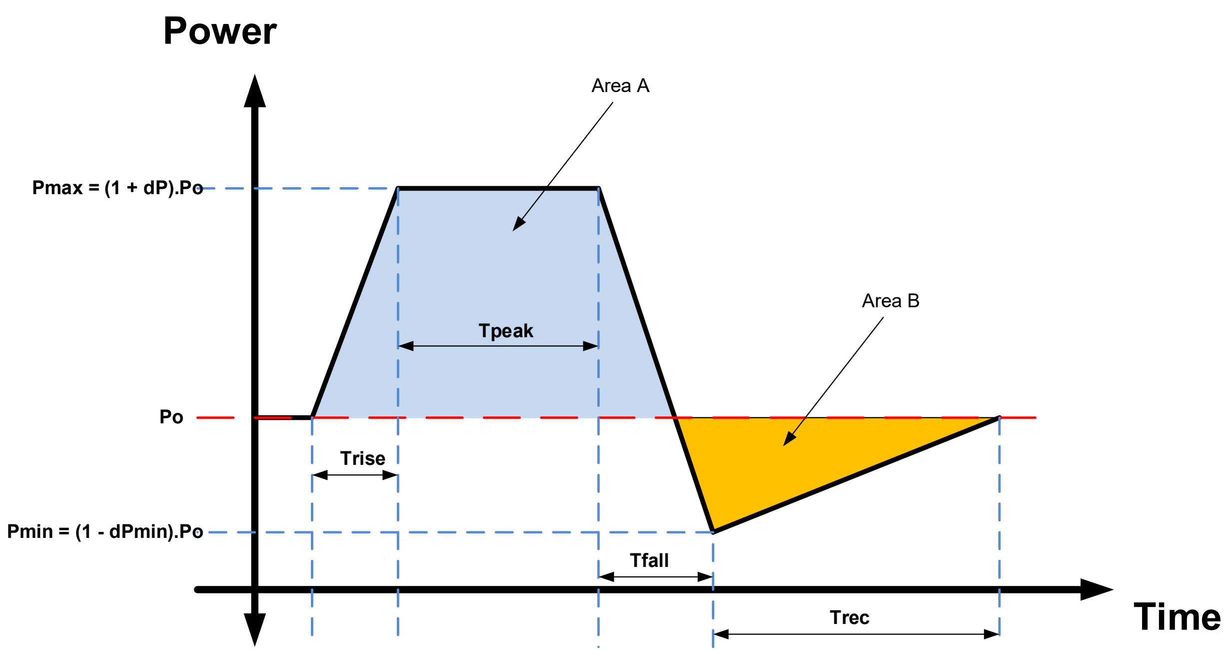


Figure 4-27
Characteristic of the IBFFR model [9]

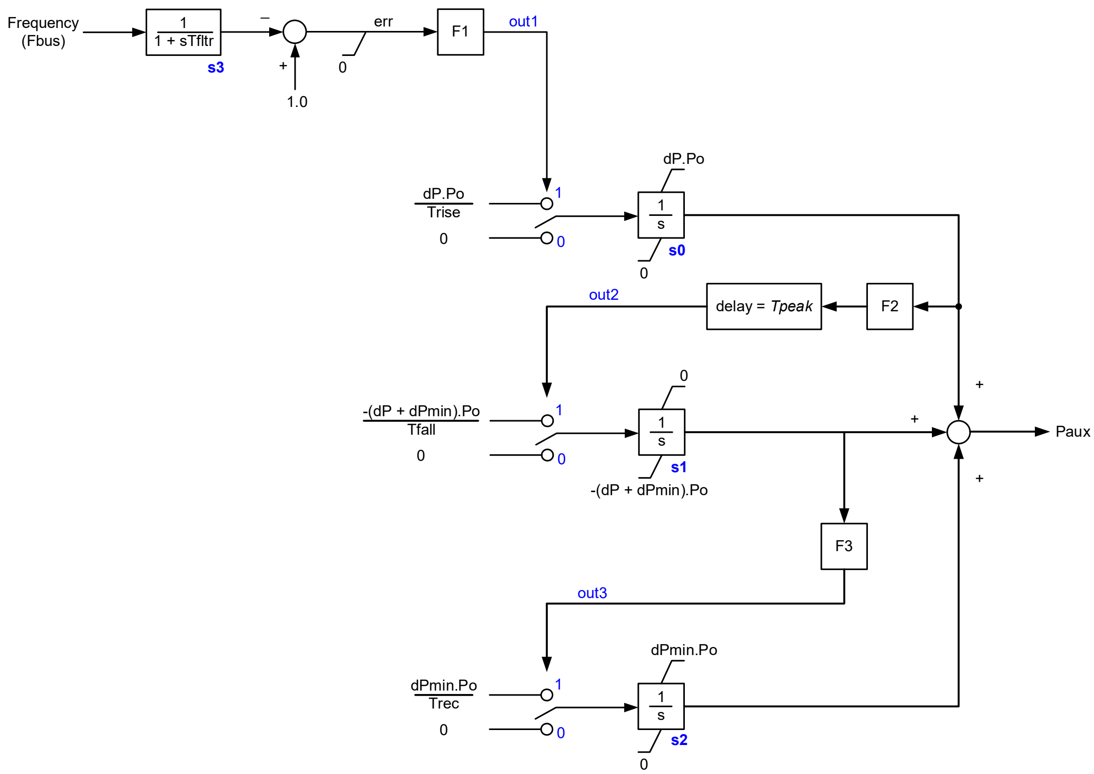


Figure 4-28
The WTGIBFFR_A model

Table 4-10
Parameter list for the WTGIBFFR_A model

Parameter Number	Parameter Name	Description	Lowest Value	Typical	Highest Value	Units
1	dbd	Deadband (≥ 0)	0.002	0.003	0.01	[pu]
2	p1	Power level 1	OEM	OEM	OEM	[pu]
3	p2	Power level 2	OEM	OEM	OEM	[pu]
4	p3	Power level 3	OEM	OEM	OEM	[pu]
5	p4	Power level 4	OEM	OEM	OEM	[s]
6	p5	Power level 5	OEM	OEM	OEM	flag
7	p6	Power level 6	OEM	OEM	OEM	[pu]
8	dP1	Per unit increase in power at power level 1	0.05	OEM	0.1	[pu]
9	dPmin1	Per unit decrease in power for recovery at power level 1	OEM	OEM	OEM	[pu]
10	Trise1	Rise time at power level 1	OEM	OEM	OEM	[s]
11	Tpeak1	Time at peak at power level 1	OEM	OEM	OEM	[s]
12	Tfall1	Fall time at power level 1	OEM	OEM	OEM	[s]
13	Trec1	Recovery time at power level 1	0	0	OEM	[s]
14	dP2	Per unit increase in power at power level 2	0.05	OEM	0.1	[pu]
15	dPmin2	Per unit decrease in power for recovery at power level 2	OEM	OEM	OEM	[pu]
16	Trise2	Rise time at power level 2	OEM	OEM	OEM	[s]
17	Tpeak2	Time at peak at power level 2	OEM	OEM	OEM	[s]
18	Tfall2	Fall time at power level 2	OEM	OEM	OEM	[s]
19	Trec2	Recovery time at power level 2	0	0	OEM	[s]
20	dP3	Per unit increase in power at power level 3	0.05	OEM	0.1	[pu]
21	dPmin3	Per unit decrease in power for recovery at power level 3	OEM	OEM	OEM	[pu]
22	Trise3	Rise time at power level 3	OEM	OEM	OEM	[s]
23	Tpeak3	Time at peak at power level 3	OEM	OEM	OEM	[s]
24	Tfall3	Fall time at power level 3	OEM	OEM	OEM	[s]
25	Trec3	Recovery time at power level 3	0	0	OEM	[s]
26	dP4	Per unit increase in power at power level 4	0.05	OEM	0.1	[pu]
27	dPmin4	Per unit decrease in power for recovery at power level 4	OEM	OEM	OEM	[pu]
28	Trise4	Rise time at power level 4	OEM	OEM	OEM	[s]
29	Tpeak4	Time at peak at power level 4	OEM	OEM	OEM	[s]
30	Tfall4	Fall time at power level 4	OEM	OEM	OEM	[s]
31	Trec4	Recovery time at power level 4	0	0	OEM	[s]
32	dP5	Per unit increase in power at power level 5	0.05	OEM	0.1	[pu]
33	dPmin5	Per unit decrease in power for recovery at power level 5	OEM	OEM	OEM	[pu]
34	Trise5	Rise time at power level 5	OEM	OEM	OEM	[s]
35	Tpeak5	Time at peak at power level 5	OEM	OEM	OEM	[s]
36	Tfall5	Fall time at power level 5	OEM	OEM	OEM	[s]
37	Trec5	Recovery time at power level 5	0	0	OEM	[s]
38	dP6	Per unit increase in power at power level 6	0.05	OEM	0.1	[pu]
39	dPmin6	Per unit decrease in power for recovery at power level 6	OEM	OEM	OEM	[pu]
40	Trise6	Rise time at power level 6	OEM	OEM	OEM	[s]
41	Tpeak6	Time at peak at power level 6	OEM	OEM	OEM	[s]
42	Tfall6	Fall time at power level 6	OEM	OEM	OEM	[s]
43	Trec6	Recovery time at power level 6	0	0	OEM	[s]
44	Tlapse	Time lapse from the end of an IBFFR cycle until IBFFR is available again	120	OEM	OEM	[s]
45	fbus	Power flow bus number where freqeuncy is measured	N/A	N/A	N/A	bus no.
46	Tfltr	Measurement/filter time constant for measured frequency	0.02	0.05	0.1	[s]

4.5 Putting the Models Together to Develop IBR Plant Models

In each commercial software platform, the software user's manual should be thoroughly consulted to become familiar with proper model instantiation, initialization and usage. That said, Table 4-11 shows which models can be used in combination to model each type of IBR plant.

The following important notes are to be considered when choosing the appropriate models in Table 4-11:

1. Only one model should be chosen in each category. For example, to build a type 3 wind plant model one may choose to use REGC_A, REEC_A, REPC_A, WTGA_A, WTGQ_A, WTGP_A and WTGT_A.
2. The Category 8 models (auxiliary/supplemental) are optional and to be used only when necessary and needed.
3. For a type 4 wind power plant, the WTGT_B model is optional, and only to be used if the particular type/model of WTG exhibits torsional oscillations in the electrical power output of the WTG after a nearby fault. Some make/models of type 4 WTG do not exhibit this behavior and so the WTGT_B should not be used in those cases (see e.g., the comparison between Figures 4-1 and 4-2 in [13]).
4. The Category 4 through 8 models are for WTGs only.

Table 4-11
Models that can be used for modeling each type of IBR plant. Note, only ONE model should be chosen in each category.

Model Name	Wind Plant Type 3	Wind Plant Type 4	PV Plant	BESS Plant
Category 1 - Generator/Converter Model				
REGC_A	√	√	√	√
REGC_B	√	√	√	√
REGC_C	√	√	√	√
Category 2 - Converter Electrical Controls				
REEC_A	√	√	√	
REEC_C				√
REEC_D	√	√	√	√
Category 3 - Power Plant Controller				
REPC_A	√	√	√	√
REPC_C	√	√	√	√
Category 4 - Aero-Dynamics				
WTGA_A	√			
Category 5 - Torque Controller				
WTGQ_A	√			
Category 6 - Pitch Controller				
WTGP_A	√			
WTGP_B	√			
Category 7 - Drive Train Shaft Dynamics				
WTGT_A	√			
WTGT_B		√ (optional)		
Category 8 - Auxilliary/Supplemental Controls				
WTGWGO_A		√ (optional)		
WTGIBFFR_A	√ (optional)	√ (optional)		

5
SUMMARY AND RECOMENDATIONS

This document provides a concise, yet hopefully comprehensive, guide to the use of the latest so-called 2^{nd} generation generic, and public, renewable energy system models for use in positive sequence stability simulation programs. These models have been adopted by four North American, and at least one European, commercial software vendors for large scale positive-sequence simulation software. Furthermore, although not discussed here, one electromagnetic transient (EMT) software vendor has also started to adopt these models, and they are also available in the power system tool box of some other software tools. Since the model specifications are public, they may very well be adopted by other software vendors too. Being public, open, well documented and not specific to any vendor, these models offer access to a means of performing simulation studies related to inverter based resources for futuristic studies, where specific equipment has not been chosen, as well as large scale inter-connected system wide studies where the detailed minutia of a given site may not be as important as the overall system performance. In any case, the models should always be carefully parameterized, and where possible in consultation with the equipment vendor, if representing an existing or soon to be built plant. Engineering judgement must always be applied to understand the focus of the study, the limitations of the models and thus whether or not they are applicable and useful for the intended use.

Finally, as the technology for inverter based generation continues to progress there is no doubt that new and enhanced models will be developed and added to this library of generic models. As such, revisions of this document will no doubt be required in the future.

6
REFERENCES

[1] *WECC Second Generation Wind Turbine Models*, January 23, 2014 https://www.wecc.biz/Reliability/WECC-Second-Generation-Wind-Turbine-Models-012314.pdf

[2] *Technical Update: Generic Models and Model Validation for Wind Turbine Generators and Photovoltaic Generation*, EPRI, Palo Alto, CA, 2013, Product ID: 3002001002 (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002001002)

[3] *Generic Models and Model Validation for Wind and Solar PV Generation: Technical Update*. EPRI, Palo Alto, CA: 2011, 1021763. (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001021763)

[4] *Proposed Changes to the WECC WT3 Generic Model for Type 3 Wind Turbine Generators*, Prepared under Subcontract No. NFT-1-11342-01 with NREL, Issued: 03/26/12 (revised 6/11/12, 7/3/12, 8/16/12, 8/17/12, 8/29/12, 1/15/13, 1/23/13, 9/27/13) https://www.wecc.org/Reliability/Report_on_WT3_Model_Description_PP012313.pdf

[5] *Proposed Changes to the WECC WT4 Generic Model for Type 4 Wind Turbine Generators*, Prepared under Subcontract No. NFT-1-11342-01 with NREL, Issued: 12/16/11 (revised 3/21/12, 4/13/12, 6/19/12, 7/3/12, 8/16/12, 8/17/12, 8/29/12, 1/15/13, 1/23/13) https://www.wecc.org/Reliability/Report_on_WT4_Model_Description_PP012313.pdf

[6] *Proposed Changes to the WECC WT1 Generic Model for Type 1 Wind Turbine Generators*, Prepared under Subcontract No. NFT-1-11342-01 with NREL, Issued: 1/21/13

[7] *Simple Model Specification for Battery Energy Storage System*, memo issued to WECC REMTF, MVWG and EPRI 173.003; 1/15/15 (REVISED 2/25/15; 3/6/15; 3/18/15) https://www.wecc.biz/Reliability/REEC_C_031815_rev3%20Model%20Spec.pdf

[8] *Model Specification for High-Level Plant Controller*, memo issued to WECC REMTF, MVWG and EPRI 173.003; 11/25/14 (REVISED 1/6/15; 1/20/15; 11/5/15) https://www.wecc.biz/Reliability/Memo-REPC-B-110515.pdf

[9] *Proposal for New Features for the Renewable Energy System Generic Models*, memo issued to WECC MVS 7/23/18 (Revision 27: 2/16/23) https://www.wecc.org/Reliability/Memo_RES_Modeling_Updates_021623_Rev27_Clean.pdf

[10] Ö. Göksu, P. Sørensen, J. Fortmann, A. Morales, S. Weigel, P. Pourbeik, "Compatibility of IEC 61400-27-1 Ed 1 and WECC 2nd Generation Wind Turbine Models", Conference: 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, November 2016.

[11] EPRI Report, Model User Guide for Generic Renewable Energy System Models, Product ID 3002014083, Jul 13, 2018. https://www.epri.com/research/products/000000003002014083

[12] CIGRE Technical Brochure 328, *Modeling and Dynamic Behavior of Wind Generation as it Relates to Power System Control and Dynamic Performance*, August 2007 (https://e-cigre.org/publication/328-modeling-and-dynamic-behavior-of-wind-generation-as-it-relates-to-power-system-control-and-dynamic-performance)

[13] P. Pourbeik, J. Sanchez-Gasca, J. Senthil, J. Weber, P. Zadehkhost, Y. Kazachkov, S. Tacke and J. Wen, "Generic Dynamic Models for Modeling Wind Power Plants and other Renewable Technologies in Large Scale Power System Studies", *IEEE Trans. on Energy Conversion*, September 2017, http://ieeexplore.ieee.org/document/7782402/

[14] E. Muljadi, C. P. Butterfield, A. Ellis, J. Mechenbier, J. Hochheimer, R.Young, N. Miller, R. Delmerico, R. Zavadil and J.C. Smith, "Equivalencing the collector system of a large wind power plant," presented at the IEEE Power Engineering Society General Meeting, Montreal, QC, June 2006.

[15] WECC Wind Plant Dynamic Modeling Guidelines, May 2008 https://www.wecc.org/Reliability/WECCWindPlantPowerFlowModelingGuide.pdf

[16] D. Ramasubramanian, P. Pourbeik, E. Farantatos and A. Gaikwad, "Simulation of 100% Inverter-Based Resource Grids With Positive Sequence Modeling", IEEE Electrification Magazine, June, 2021. https://ieeexplore.ieee.org/document/9447546

[17] D. Ramasubramanian, Z. Yu, R. Ayyanar, V. Vittal and J. M. Undrill, "Converter Model for Representing Converter Interfaced Generation in Large Scale Grid Simulations", IEEE Trans. PWRS, April 2016.

[18] D. Ramasubramanian, W. Wang, P. Pourbeik, E. Farantatos, A. Gaikwad, S. Soni and V. Chadliev, "A Positive Sequence Voltage Source Converter Mathematical Model for Use in Low Short Circuit Systems", IET Generation, Transmission & Distribution, January 2020. https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-gtd.2019.0346

[19] P. Pourbeik and J. K. Petter, "Modeling and validation of battery energy storage systems using simple generic models for power system stability studies", *CIGRE Science and Engineering*, October 2017, pp. 63-72. (available for free download at https://e-cigre.org/)

[20] P. Pourbeik, D. J. Sullivan, A. Boström, J. Sanchez-Gasca, Y. Kazachkov, J. Kowalski, A. Salazar, A. Meyer, R. Lau, D. Davies and E. Allen, "Generic Model Structures for Simulating Static Var Systems in Power System Studies—A WECC Task Force Effort", IEEE Transactions on PWRS, August 2012. https://ieeexplore.ieee.org/document/6142134

[21] P. Pourbeik, S. Soni, A. Gaikwad and V. Chadliev, "Providing Primary Frequency Response from Photovoltaic Power Plants", CIGRE Science and Engineering, October 2018.

[22] *Proposal for New Plant Controller and Electrical Controller*, issued to WECC MVS on 5/13/22 (REVISED 9/19/22; 2/6/23; 7/5/23; 8/02/23).

[23] W. W. Price and J.J. Sanchez-Gasca, "Simplified Wind Turbine Generator Aerodynamic Models for Transient Stability Studies" Proc. IEEE PES 2006 Power Systems Conference and Exposition (PSCE), Oct. 29-Nov. 1, 2006, Atlanta, GA, pp. 986-992.

[24] H. Ma and J. Nielsen, "Siemens Wind Plant Inertial Response Modeling in PSSE WECC library", presented to the WECC MVWG in June 2016.

[25] D. Caldas, M. Fischer and S. Engelken, "Inertial Response Provided by Full-Converter Wind Turbines", Proceedings of the Brazil Wind Power Conference and Exposition, 2015. http://www2.ctee.com.br/brazilwindpower/2015/papers/Danilo_Caldas.pdf

[26] P. Pourbeik, "Example Verification of the Proposed IBFFR Model", Memo issued to WECC REMTF and EPRI, 7/17/19.
https://www.wecc.org/Reliability/Memo_IBFFR_071719.pdf

A

CURRENT LIMIT LOGIC FOR REEC_A

VDL1 is a piecewise linear curve define by four pairs of numbers:
{(vq1, Iq1), (vq2, Iq2), (vq2, Iq3), (vq4, Iq4),}

VDL2 is a piecewise linear curve define by four pairs of numbers:
{(vp1, Ip1), (vp2, Ip2), (vp2, Ip3), (vp4, Ip4),}

If (Pqflag = 0) *Q – priority*

$$Iqmax = \min\{VDL1, Imax\}$$

$$Iqmin = -1 \times Iqmax$$

$$Ipmax = \min\{VDL2, \sqrt{Imax^2 - Iqcmd^2})$$

$$Ipmin = 0$$

Else *P – priority*

$$Iqmax = \min\{VDL1, \sqrt{Imax^2 - Ipcmd^2}\}$$

$$Iqmin = -1 \times Iqmax$$

$$Ipmax = \min\{VDL2, Imax)$$

$$Ipmin = 0$$

End

B

CURRENT LIMIT LOGIC FOR REEC_D

REEC_D has ten (10) pairs of points for each of the VDL tables, namely:

VDLq reactive-current limits = {(iq1, vq1), (iq2, vq2), (iq3, vq3), (iq4, vq4), (iq5, vq5), (iq6, vq6), (iq7, vq7), (iq8, vq8), (iq9, vq9), (iq9, vq9), (iq10, vq10)}

VDLp active-current limits = {(ip1, vp1), (ip2, vp2), (ip3, vp3), (ip4, vp4), (ip5, vp5), (ip6, vp6), (ip7, vp7), (ip8, vp8), (ip9, vp9), (ip9, vp9), (ip10, vp10)}

The *iq's* can be positive or negative

The *ip's* must all be greater than or equal to zero

Furthermore,

If (Pqflag = 0) Q – priority

Iqmax = min {VDLq, Imax}

If Iqmax < 0

Iqmin = Iqmax (important new logic)

else

Iqmin = -1 × Iqmax

end

Ipmax = min {VDLp, $\sqrt{Imax^2 - Iqcmd^2}$}

Ipmin = -Ke × Ipmax (important new logic)

else P – priority

Iqmax = min {VDLq, $\sqrt{Imax^2 - Ipcmd^2}$}

If Iqmax < 0

Iqmin = Iqmax (important new logic)

else

Iqmin = -1 × Iqmax

end

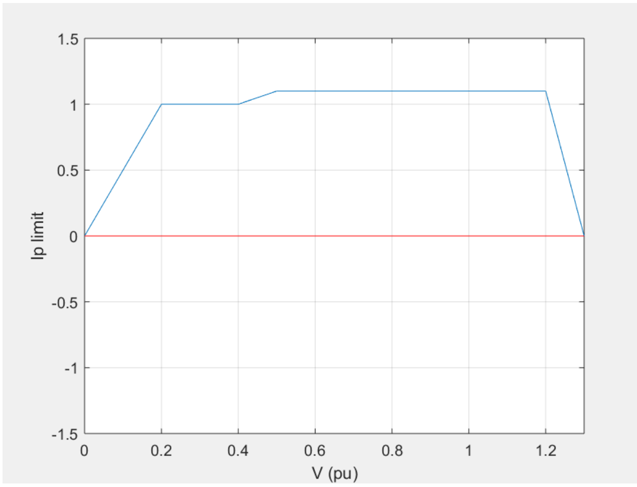
Ipmax = min {VDLp, Imax}

Ipmin = -Ke × Ipmax (important new logic)

end

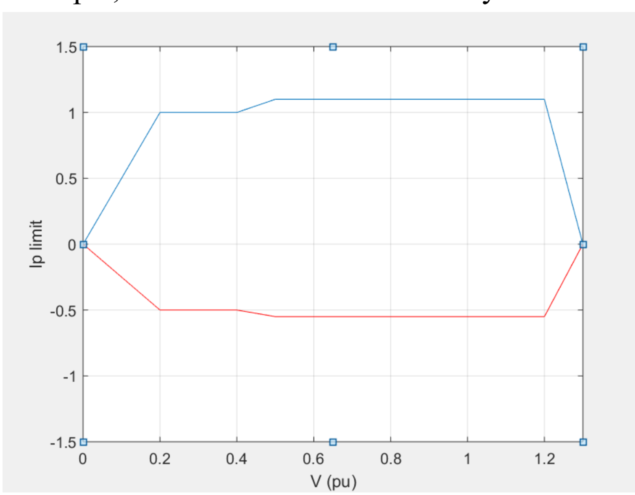
The explanation for the new logic (marked in green comments) above is as follows:

- If Ke = 0, then the model mimics a generator, that is Ipmin = 0 and the unit cannot absorb active power from the grid. As an illustrative example, here is what such a case may look like:



where the BLUE line depicts the 10 pairs of points for VDLp, and the RED line is the derived Ipmin, which is zero in this case because Ke = 0.

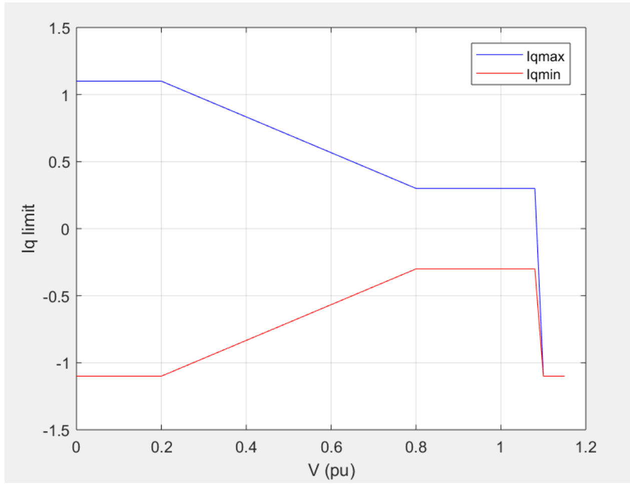
- If (1 ≥ Ke > 0), then the model mimics a storage device, that is capable of also absorbing active current. A value of Ke < 1 implies that the device has a lower capacity for absorbing instantaneous power, as compared to its capacity of generating instantaneous power. As an illustrative example, here is what such a case may look like:



where the BLUE line depicts the 10 pairs of points for VDLp, and the RED line is the derived Ipmin, which is less than Ipmax in magnitude in this case because Ke = 0.5 (less than 1).

- Ke cannot be negative or greater than 1.
- In the case that Iqmax is negative, then Iqmin must also be negative and the same value in order to force Iqcmd to this limit. This is used in some cases during extreme high voltages to

make the inverter absorb reactive power. As an illustrative example, here is what such a case may look like:



About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

3002027129

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com