User Manual for Fluence Battery Energy Storage

Power Plant Controller Model

PSS®E MANUAL

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Revision History

Version Number	Date	Author	Section/Page	Description
R9_0_0	29.01.23	HR/KA	All	Initial Report/Minor modifications
R9_0_1	31.01.24	HR	Parameters Table	Minor Modifications
R9_1_1	02.07.2023	KA	Section 3.8 – Grid Forming Plant Controls	Description added
R92_1_1	29.10.2024	KA	Section 3.9 – Parameters Table	Remote voltage measurement bus number for FRT
R10_0_0	09.12.2024	KA	Section 3.9 (Parameter Table) and 3.10 (USRBUS model)	Updated parameter list and PPC model as USRBUS model
R1010	29.01.2025	TPV	Section 2, Section 3.9 (Parameter Table) and 3.10 (USRBUS model)	Updated parameter list and updated the PPC model with point of control of power and Individual set points for different inverter.
R1010	14.04.2025	KA	Section 3.3	Note for RPCM = 5 mode
R1011	17.03.2025	TPV	Section 3.9 (Parameter Table)	Added the ICON for Inverter Interface
R1012	27.05.2025	TPV	Section 3.9 (Parameter Table) and 3.10 Dynamic File	Improvement in FRT logic and Bug Fixed in Reverse metering
V1020	06.06.2025	TPV	Section 2, Section 3.0, 3.9(Parameter Table) and 3.10 (Dynamic File)	PPC Model (Uniform) for Generator/ Machine represented as WMOD = 0 and WMOD = 1-3

Contents

1. Introduction

This document is a User Manual for the PSS®E Version 33, 34,35 and 36 user-defined model (UDM) of the Fluence Battery Energy Storage System (BESS) Power Plant Controller (PPC) based on the control strategy developed by Fluence, intended for use in load flow and stability studies. The model represents solely the PPC and can be used with different generator and electrical models that are modeled as either a 'Not a wind machine' (WMOD = 0) or a 'wind machine' (WMOD = 1 – 3). The purpose of the PPC UDM is to integrate with the Power Conversion System (PCS) or Inverter model e.g. Power Electronics[1] dynamic model locally for the BESS, as well as send commands to an additional optional external project.

Batteries, being DC units, are typically integrated into the AC system through inverters, step-up transformers and other components to convert battery stored energy to grid-quality AC energy for delivery at transmission or distribution voltage.

The PPC UDM consists of the following with the PSS®E version denoted by XX:

- The model dynamics file FLNPPC_V1020.dyr
- The model DLL file FLUENCE_vXXX_V1020.dll

The generator should be connected to a 0.48kV/0.69 kV bus or a bus with the voltage outlined within the PCS/Inverter e.g. Power Electronics model documentation. The PPC UDM provides the following capabilities:

- Remote active power control
- Local active/reactive power control for battery/external project
- Power firming dispatch
- Frequency droop control (local or remote)
- Low Frequency Demand Disconnection
- Voltage droop control (local or remote)
- Dynamic reactive power control (local or remote)
    - Power factor control
    - Voltage control
- Joint reactive power control

[1] Power Electronics PE_PSSE_PCSK_P1000a_R01

- Synthetic Inertia
- Power Oscillation Damping
- Grid Forming Plant Controls

2. Load Flow Modeling

The BESS is modeled as a generator utilizing the typical inverter in the PSS®E load flow case connected to a P/V bus (PSS®E Type 2). A BESS inverter can be modeled either as a Standard machine i.e. 'not a wind machine' (WMOD = 0) or as a 'wind machine' (WMOD = 1–3), depending on the inverter model. This record is found in the Machine's Network Data Record. The external project may be set as either a 'Not a wind machine' (WMOD = 0) or a wind machine (WMOD = 1 – 3), depending on the dynamic models associated to the project.

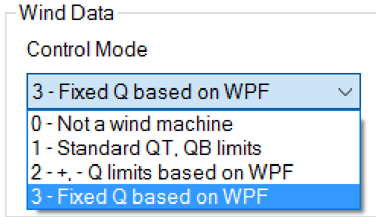

Figure 1 : Control Mode

It is the user's responsibility to model the equipment that is utilized for the project within the load flow case. This includes but is not limited to padmount transformers, collection system, main power transformer (MPT), etc.

The inverter converts the DC power provided by the battery to the desired voltage of the inverter. For utility-scale or transmission interconnection applications, the BESS will be normally connected through a step-up transformer which converts the low voltage to medium voltage and potentially an MPT which converts the medium voltage to transmission level voltage.

The parameters of a single Fluence BESS string modeled as a generator in the load flow case are shown in Table 1 based on the Power Electronics inverter.

Table 1. Load Flow Parameters of a Single BESS

Parameter	**Value**	**Unit**
Vrated	0.69	kV
Inverter base	4390	kVA
Resistance	0.01	per unit on inverter base
Reactance	0.05	per unit on inverter base
Pmax	4390	kW
Pmin	-4390	kW

The BESS model can be used to represent a number of identical BESS strings. The parameters for “N” BESS strings modeled as a single generator in the load flow case are shown in Table 2.

Table 2. Load Flow Parameters of a Group (N) of BESS Strings

Parameter	Value	Unit
Vrated	0.69	kV
Inverter base	4390*N	kVA
Resistance	0.01	per unit on inverter base
Reactance	0.05	per unit on inverter base
Pmax	4390*N	kW
Pmin	-4390*N	kW

In the FLNCPPC dynamic parameters the different generator buses need to be indicated by means of the ICONS range M+22 to M+51 for a maximum number of 30 generators in total. This ensures correct communication among PPC and all generators during dynamic simulation. ICON (M+3) defines the branch power reference at the point of interconnection (POI): a value of 0 indicates that power will be measured from the FROM BUS, while a value of 1 indicates that power will be measured from the TO BUS.

3. Dynamic Modeling

The BESS is comprised of a battery and an inverter. The battery is modeled using algebraic and dynamic equations of battery energy, state of charge (SOC), charge/discharge resistance and open circuit voltage. The inverter is not included within the UDM, however its associated active and reactive power controllers in addition to current and power limiters are included within the PPC UDM. The developed PPC is used to control active and reactive power references to the battery inverter model and an optional external project model. The control diagrams for the BESS PPC UDM, as utilized to develop the PSS®E UDM, are shown in Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6 respectively. The sections below explain each of the control functions of the PPC included within the block diagram. The PPC UDM will need to be connected to a generator and electrical model in order to be used in PSS®E.

For generators represented as a Standard machine i.e. non-wind machines (WMOD = 0) in the load flow, set ICON(M+58) = 1. For wind machines (WMOD = 1–3) in the load flow, set ICON(M+ 58) = 2. For the inverter interface of a wind machine, when represented using an electrical control model, set ICON(M+ 57) = 1 (default); when represented using a generator model, set ICON(M + 57) = 2.

3.1 Battery Model

The battery model, shown in Figure 2, tracks the state of charge (SOC) of the battery. The battery measurement PBAT is passed through an integrator that serves to either represent charging or discharging of the battery. The user may control the rate at which the battery charges or discharges with CON (J+16). If the charge/discharge logic allows, the active power output PREF, originating from the PPC, will be passed to the PSS®E internal array WPCMND(WMC). This signal is shown by PREFINT.

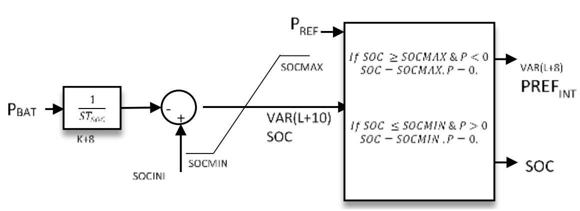

Figure 2 Battery Model

3.2 Active Power Controller

The active power controller is responsible for commanding the active power reference to the battery model (PREF) and an optional external project (PREFEXT). The external active power reference (PREFEXT) may be used to command either a project represented as WMOD = 1 – 3[2], by setting ICON (M+13) to 1, or WMOD = 0[3], by setting ICON (M+13) to 2. The PTI internal arrays to be updated would be PQCMND(WMC2) or EFD(MC2) for a project represented as a WMOD = 1 – 3 or WMOD = 0 respectively.

The available active power control modes allow one to generate these local active power references of the battery model (PREF) and external project (PEXTREF) with manual dispatch commands (PLCLCMD) and (PLCLCMDEXT) respectively. A remote branch active power command (PRMTCMD) may be used to generate the power reference of the battery model (PREF). The PREF and PEXTREF references may be generated through a joint remote branch active power command (PRMTFRMCMD). The PPC UDM also incorporates a stackable frequency droop control which can be leveraged along with the activated active power dispatch mode. Each of these control modes are shown in Figure 3 and Figure 4 with further description below.

The local active power control mode may be enabled by setting PRCF via ICON (M+6) to 1. The local active power command PLCLCMD may be set through VAR (L+2). This logic may be used alongside the stackable frequency logic, discussed later in this section. The optional external project active power command PLCLCMDEXT may also be specified with VAR (L+12), however will not participate in the stackable frequency logic.

The remote active power control mode may be enabled by setting PRCF via ICON (M+6) to 2. The branch at which the active power is controlled will be set by ICON (M) – ICON (M+2). The active power measurement at this branch may be delayed by setting TPM at CON (J+3). The difference between the remote active power command (PRMTCMD), set with VAR (L), and the remote branch active power measurement will drive the integrator which has the gain TPI specified by CON (J+10). The output of the PI will be summed with the remote active power command PRMTCMD after passing through a feed forward gain set by KPFF at CON (J+9). The user may limit the contribution from the integrator with PMININT and PMAXINT set by CON

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[2] Logic tested with the Power Electronics provided PE_PSSE_PCSK_P1000a_R01 controller and inverter models

[3] Logic tested with the SMA provided SMASC_E147 inverter model

(J+52) and CON (J+51) respectively. PRMTCMD may be modified by enabling the Frequency Stack Logic or FSL. The sum of PRMTCMD and FSL cannot exceed the maximum export or import capacity of the BESS plant at the point of connection (POC). This is therefore set with PMAXPOC and PMINPOC at CON(J+78) and CON(J+79) respectively.

The optional external project active power command PLCLCMDEXT may also be specified with VAR (L+12), however will not participate in the stackable frequency logic.

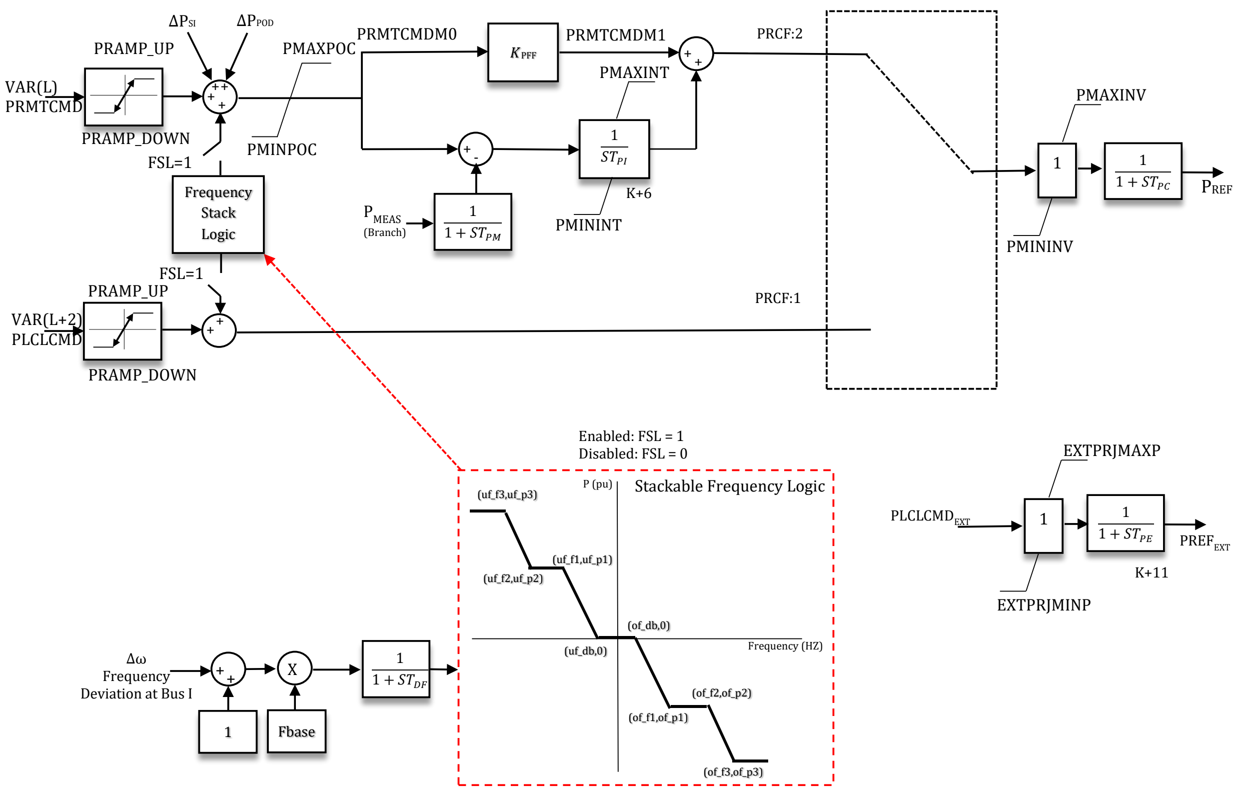

Figure 3 Active Power Controller Mode 1 and 2

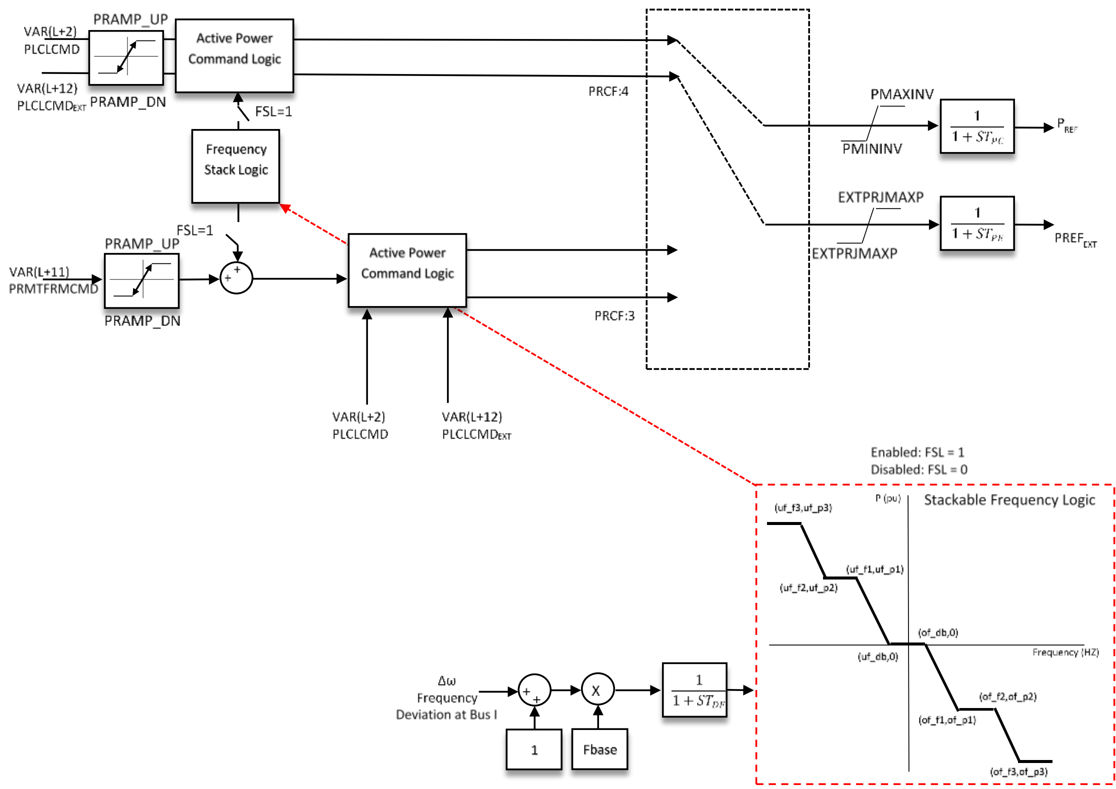

Figure 4 Active Power Controller Mode 3 and 4

The joint active power firming control may be enabled by setting PRCF via ICON (M+6) to 3. This mode attempts to maintain a constant active power at a remote branch through active power references to both the battery and external project models. The relevant branch will be set through ICON (M) – ICON (M+2). The active power measurement at this branch may be delayed by setting TPM at CON (J+3). The external project bus number and ID are set via ICON (M+11) and ICON (M+12). The remote branch active power command (PRMTFRMCMD) will be summed with the output of the stackable frequency logic, if enabled, for an end branch command and fed into a priority block. ICON (M+10) may be set to 0 for battery priority or 1 for external project priority. Any changes to the end branch command will be handled by the prioritized project until the associated project's limits are reached. Upon reaching limits, the alternate project will take over to handle the remaining active power necessary to achieve the branch command or until the alternate project's limits are reached. The minimum and maximum limits for the battery model are set via CON (J+47) and CON (J+48). The minimum and maximum limits for the external project model are set via CON (J+68) and CON (J+69).

The joint active power control may be enabled by setting PRCF via ICON (M+6) to 4. This logic allows local active power control of both the battery and external project models via PLCLCMD and PLCLCMDEXT respectively. These signals may be used alongside the stackable frequency logic in which a priority is implemented to determine the contribution of the frequency logic to each project. ICON (M+10) may be set to 0 for battery priority or 1 for external project priority. The additional active power from the frequency logic will be summed with the prioritized project's local active power command, adhering to limits, to generate the end command to the project. If the prioritized project hits capacity limits, the alternate project will contribute the remainder until hitting its own capacity limits. The minimum and maximum limits for the battery model are set via CON (J+47) and CON (J+48). The minimum and maximum limits for the external project model are set via CON (J+68) and CON (J+69).

The stackable frequency logic, enabled by setting FSL at ICON (M+8) to 1, modifies the relevant active power commands based on the frequency. The frequency may be measured at a local or remote bus by setting ICON (M+3) to the relevant bus number or 0 for local. The frequency measurement is delayed by setting TDF at CON (J+11). The amount of active power (p.u.) contributed based on the frequency (Hz), may be set by CON (J+31) through CON (J+44) through a piece-wise function.

The end active power reference will be limited by PMAXINV and PMININV, set with CON (J+47) and CON (J+48) respectively. This reference, PREF will be sent to the battery model which will be used to generate the end battery active power reference (PREFINT). The external project active power reference will be limited by EXTPRJMAXP and EXTPRJMINP, set with CON (J+68) and CON (J+69) respectively, to generate the end external project active power reference (PREFEXT).

3.3 Reactive Power Controller

The reactive power can be controlled either using a voltage reference command (VCMD), a power factor command (PFCMD), a local/remote Q reference with voltage stackable logic (VSL) or a remote voltage setpoint with voltage stackable logic (VSL). Control functionality may be referenced in Figure 5. The VCMD mode is activated if the Reactive Power Control Mode (RPCM) ICON (M+5) is set to 1 while the PFCMD mode is activated if the flag RPCM is set to 2. Remote Q control may be enabled if RPCM is set to 3 and Local Q control may be enabled with RPCM set to 4. Remote voltage control with VSL control may be enabled with RPCM set to 5. For RPCM set to 5, the VSL control is required to be enabled by setting ICON (M+7) set to 1. Control modes 3 and 4 may also use a VSL control, enabled via VSL set by ICON (M+7). The output to the PPC reactive power controller (QPPCOUTW) will be passed to the joint reactive power controller seen in Figure 6 which will divide the reactive power reference between the battery and optional external project.

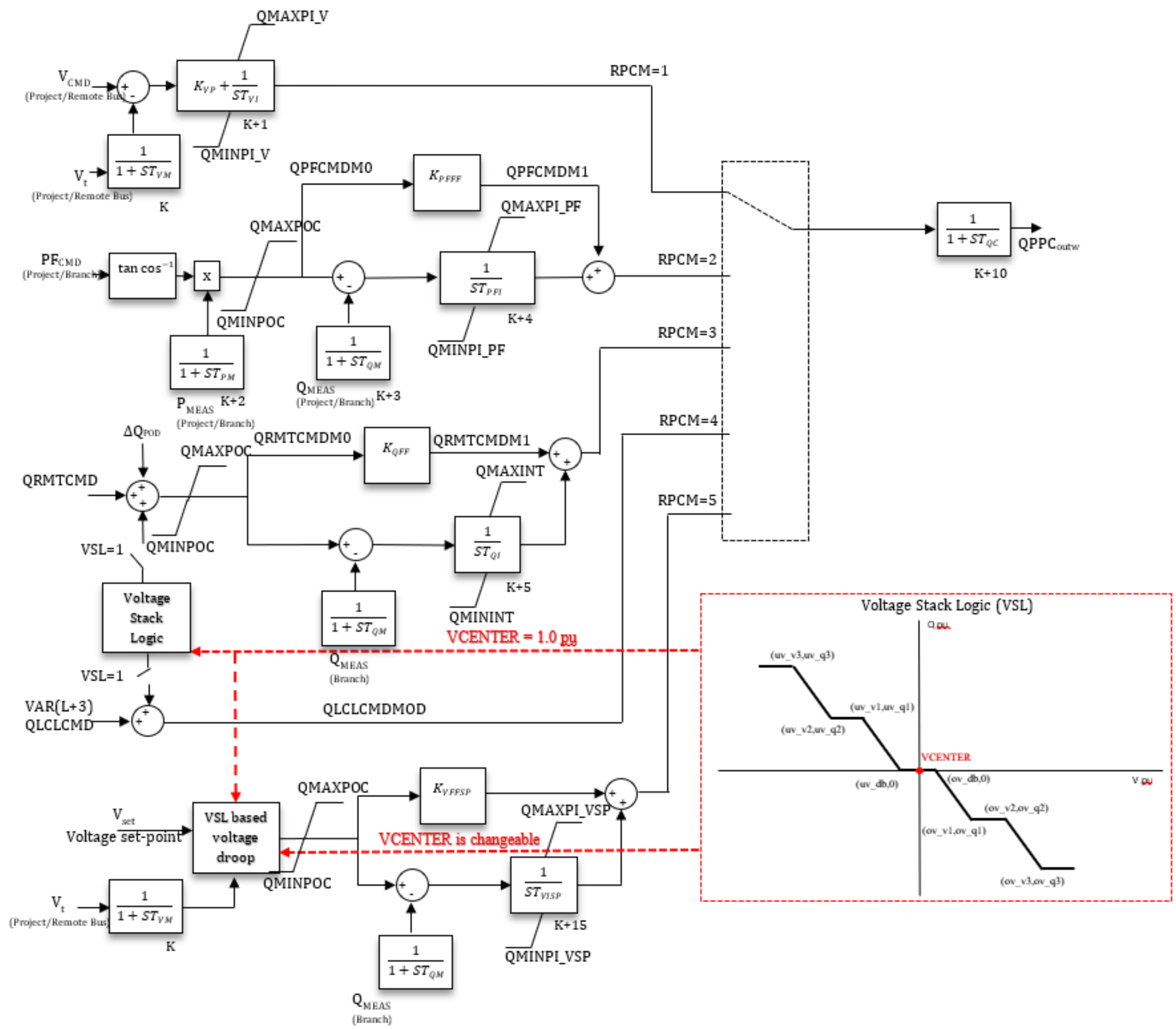

Figure 5 Reactive Power Controller

Voltage control may be enabled by setting RPCM to 1. The voltage of a local or remote bus will be controlled by changing the reference Q to the inverter. The voltage may be measured at a local or remote bus by setting ICON (M+7) to the relevant bus number or 0 for local. The voltage may be delayed by setting TVM via CON (J+2). This measurement is subtracted from the voltage command VCMD, set with VAR (L+6). The difference is fed into a PI controller with proportional and integrator gains of KVP CON (J) and KVI CON (J+1) respectively. The user may set QMINPI and QMAXPI to avoid windup with CON (J+54) and CON (J+53) respectively.

Power factor control may be enabled by setting RPCM to 2. The reactive power at a local or remote branch will be controlled to adhere to a commanded power factor. The reactive power may be measured at a local or remote branch by setting ICON (M) to ICON (M+2) to the from bus, to bus, and circuit ID of the branch, or 0 for local. The active and reactive powers may be delayed by setting TPM and TQM via CON (J+3) and CON (J+4) respectively. The power factor command PFCMD may be set by VAR (L+7). PFCMD and the active power are used to get the reactive power command. The total reactive output of the plant at its POC is limited by QMAXPOC and QMINPOC set at CON(J+80) and CON(J+81). This reactive power command is subtracted by the reactive power measurement at the local or remote location. The result is passed into an Integrator which has the integral gain time constant of TPFI set with CON(J+6). The user may set QMINPI and QMAXPI to avoid windup for this Integrator with CON (J+54) and CON (J+53) respectively. The user may also decide to perform a feed forward approach by tuning KPFFF, set by CON (J+5), to non-zero. The output of the Integrator and feed forward logic summed together represent the non-limited reactive power reference.

The remote reactive power control mode may be enabled by setting RPCM to 3. The branch at which the reactive power is controlled will be set by ICON (M) – ICON (M+2). The reactive power measurement at this branch may be delayed by setting TQM at CON (J+4). The difference between the remote reactive power command (QRMTCMD), set with VAR (L+1), and the remote branch reactive power measurement will drive the integrator which has the gain TQI specified by CON (J+8). The output of the PI will be summed with the remote reactive power command (QRMTCMD) after passing through a feed forward gain set by KQFF at CON (J+7). The user may limit the contribution from the integrator with QMININT and QMAXINT set by CON (J+50) and CON (J+49) respectively. QRMTCMD may be modified by enabling the VSL, discussed later in this section. The sum of QRMTCMD and VSL output is limited to the total reactive output of the plant by QMAXPOC and QMINPOC set at CON(J+80) and CON(J+81).

The local reactive power control mode may be enabled by setting RPCM to 4. The local reactive power command QLCLCMD may be set through VAR (L+2). This logic may be used alongside the VSL.

VSL is enabled by setting ICON (M+7) to 1, modifies the relevant reactive power commands based on the voltage. The voltage may be measured at a local or remote bus by setting ICON (M+4) to the relevant bus number or 0 for local. The voltage measurement is delayed by setting TVM at CON (J+2). The amount of reactive power (p.u.) contributed based on the voltage (p.u.), may be set by CON (J+17) through CON (J+30).

The remote voltage control mode with VSL droop control may be enabled by setting RPCM to 5. The amount of reactive power (p.u.) contributed based on the voltage (p.u.), may be set by CON (J+14) to CON (J+15) and CON (J+55) to CON (J+56). The remote voltage setpoint, Vset, may be set through VAR (L+18). In order to use this control mode the VSL is required to be always enabled by setting ICON (M+7) to 1. This control mode determines the reactive power command sent to the inverter. The reactive power is calculated based on the voltage setpoint, Vset VAR (L+18), the droop center, Vcntr CON (J+77) and the measured voltage at the remote bus. The reactive power from VSL becomes the reference for the control loop with an integrator, TVISP, and feed-forward gain, KVFFSP. VSL's reactive power output is also limited to the total reactive output of the plant by QMAXPOC and QMINPOC set at CON(J+80) and CON(J+81) respectively.

Note: Please note that the load flow case (PSS/E SAV case file) should be set up in such a way that reactive power output of the BESS plant does not exceed the QMINPOC or QMAXPOC. This would align the operating point of the plant with the minimum and maximum values provided in CON(J+21) to CON(J+23) and CON(J+28) to CON(J+30) thereby avoiding any DSTATE issues for RPCM = 5.

3.4 Joint Reactive Power Controller

The joint reactive power controller makes use of the PPC reference reactive power (QPPCOUTW) produced by the reactive power controller and creates the end reactive power references to the battery model (QCMDINT) and external project (QCMDEXT). The internal reactive power reference to the battery (QCMDINT) will update the WQCMND(WMC) array associated to the local battery machine. The external reactive power reference (QREFEXT) may be used to command either a project represented by WMOD = 1 – 3[4], by setting ICON (M+13) to 1, or WMOD = 0[5], by setting ICON (M+13) to 2. The PTI internal arrays to be updated would be WQCMND(WMC2) or XADIFD(MC2) for a project represented as a wind machine or 'Not a wind machine' respectively. Control functionality may be referenced in Figure 6.

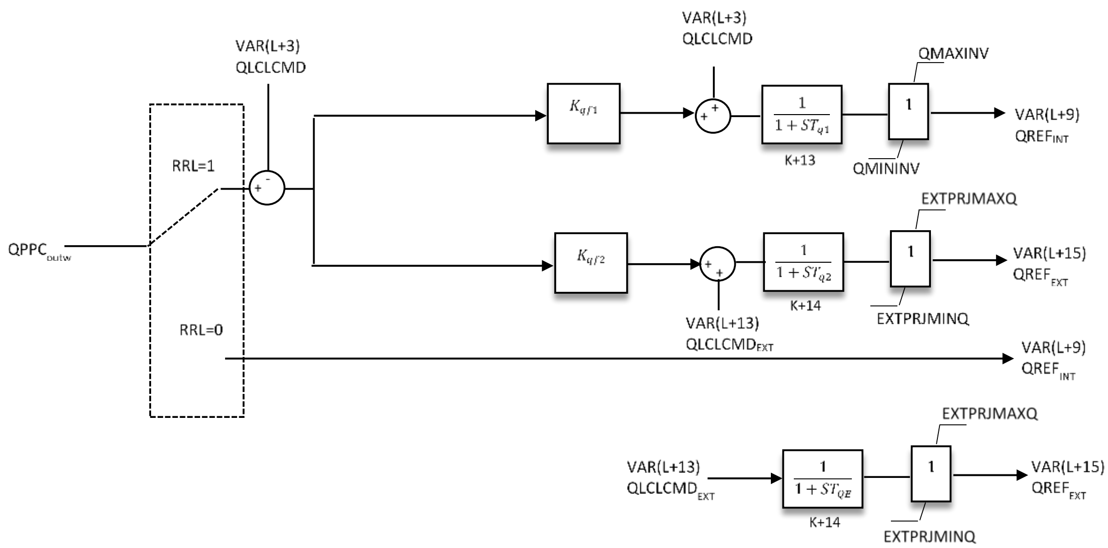

Figure 6 Joint Reactive Power Controller

When RRL is set to 0 via ICON (M+9), the output of the reactive power controller (QPPCOUTW) becomes the end reactive power reference for the battery model (QCMDINT). The external project reactive power command (QLCLCMDEXT) is fed through a delay block and limited by EXTPRJMINQ and EXTPRJMAXQ, set by CON (J+71) and CON (J+70) respectively, to obtain the external project reactive power reference QCMDEXT.

When RRL is set to 1 via ICON (M+9), the battery reactive power command (QLCLCMD) is subtracted from the output of the reactive power controller (QPPCOUTW). This supplemental reactive power, which should initialize to 0.0, will be split into two paths. Each path will represent either the battery or external project supplemental participation. The supplemental reactive power will be multiplied by the participation factors for the battery and external project, specified via CON (J+72) and CON(J+73). The battery supplemental

[4] Logic tested with the Power Electronics provided PE_PSSE_PCSK_P1000a_R01 controller and inverter models

[5] Logic tested with the SMA provided SMASC_E147 inverter model

contribution will be added to the battery reactive power command (QLCLCMD). This end command will be passed through a delay block with a delay constant TQ1 set by CON (J+74). The delayed battery end command will be limited by QMININV and QMAXINV, specified by CON (J+46) and CON (J+45) to create the end reactive power reference for the battery model (QCMDINT). The external project supplemental contribution will be added to the external project reactive power command (QLCLCMDEXT). This end command will be passed through a delay block with a delay constant TQ2 set by CON (J+75). The delayed external project end command will be limited by EXTPRJMINQ and EXTPRJMAXQ, set by CON (J+71) and CON (J+70) to create the end reactive power reference for the external project model (QCMDEXT).

It is important to note that the output of the reactive power controller (QPPCOUTW) is normally the reference to the battery model. As a result, the local reactive power command to the battery (QLCLCMD) is subtracted from this output to feed into our participation logic. This method allows each project to initialize to their respective steady state reactive power outputs and allow any additional reactive power to be split based on participation factors.

The end reactive power reference for the battery model (QCMDINT) will be used to update the battery model PSS®E array WQCMND(MC). The end reactive power reference for the external project model (QCMDEXT) will be used to update the external project model PSS®E array WQCMND(MC2).

3.5 Low Frequency Demand Disconnection

The UK's grid code introduces specific requirements for the performance of BESS during charging operation and under-frequency events. Reduction of charging active power is required for scenarios in which frequency measurements drop under a certain value. This function must work in conjunction with other frequency response controls and one of its main characteristics is that the linear reduction of charging power is dependent on the charging active power setpoint prior the underfrequency event (Pset as shown in

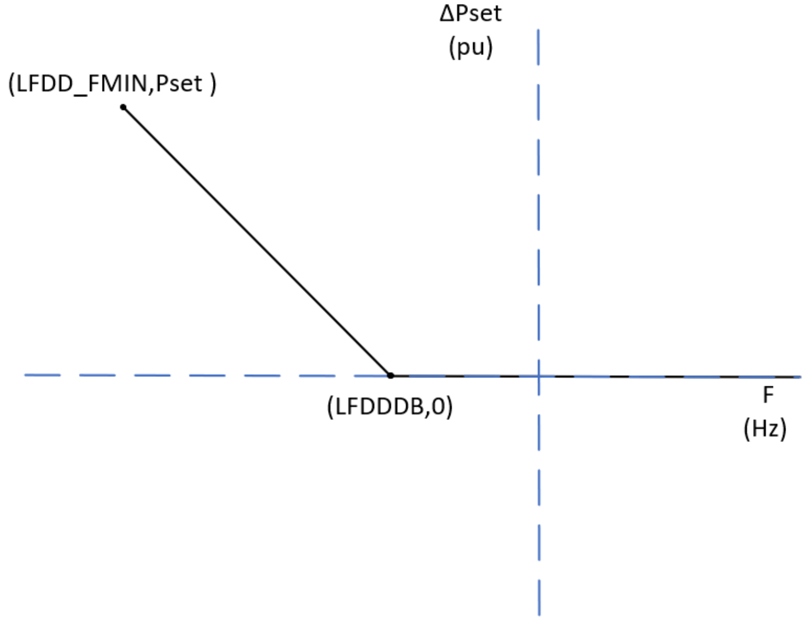

Figure 7). In the FLNC PPC model this logic is activated by setting the parameter LFDD to 1. The starting frequency for the LFDD is defined by means of the parameter LFDDDB, while the parameter LFDD_FMIN is used to define the other end of the LFDD function . As an example, in case a frequency equal or lower than LFDD_FMIN is measured at POI, the charging power will be reduced to 0.

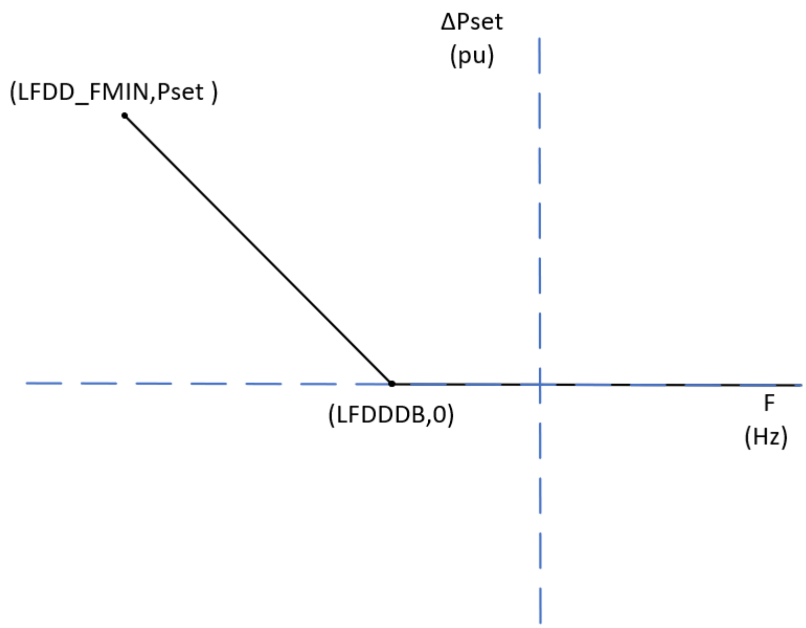

Figure 7 LFDD definition

3.6 Synthetic Inertia

The SI (Synthetic Inertia) feature enables the BESS system to regulate an inertial active power response upon RoCoF (Rate of Change of Frequency) events. The SI response is configured by means of a stackable logic that provides a temporary active power reference increment as a function of the sensed frequency variation in Hz/s. Depending on DM parameter, the discontinuous mode of the SI stackable logic can be enabled. DM=1 introduces a deadband ranging from NDFDTF1 to PDFDTF1 as shown in Figure 8. On the other hand, if DM=0 no deadband is considered (Figure 9).

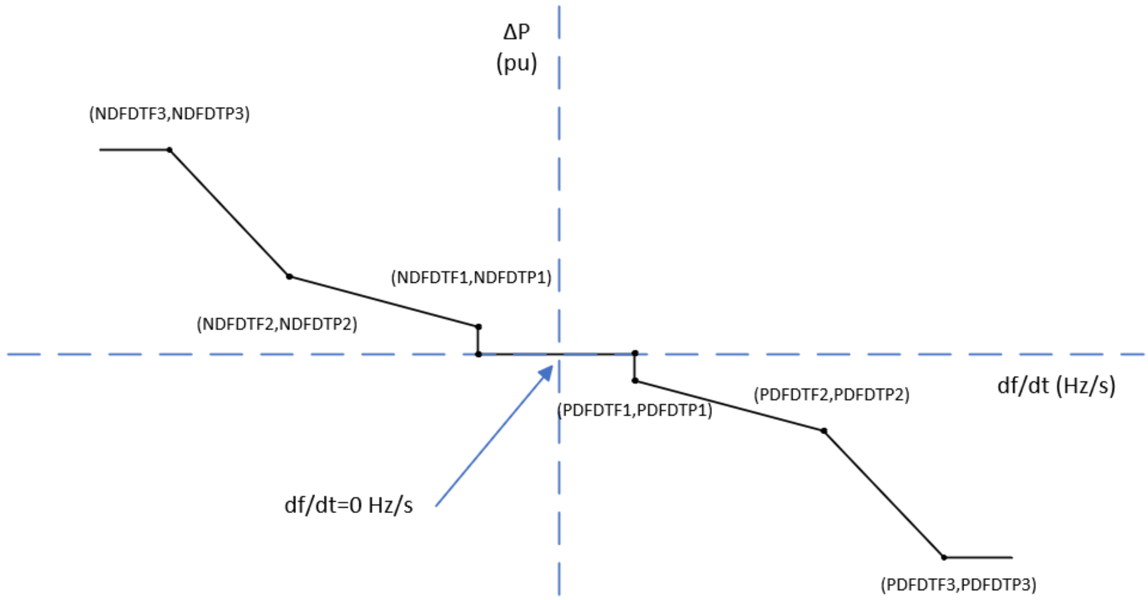

Figure 8 SISL Discontinuous mode enabled

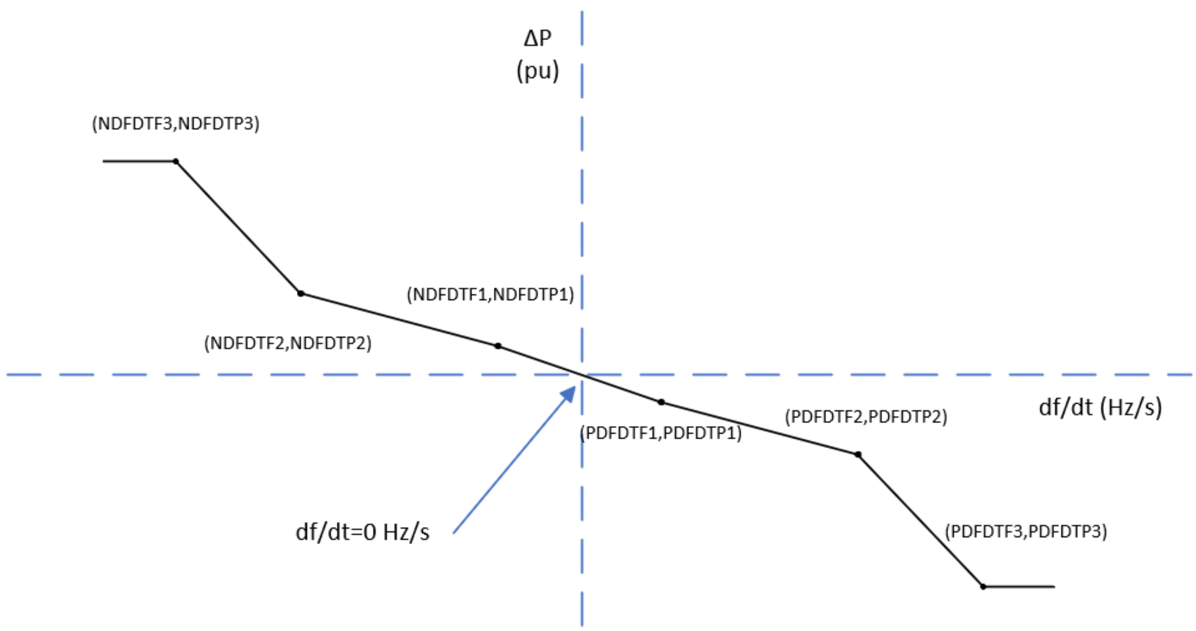

Figure 9 SISL Discontinuous mode disabled

The ΔP outcome from the previous curves is added to the external P remote command after the ramp rate control for the PRCF=2. Also, it must be highlighted that an approximate rolling average is applied for the derivative of the frequency calculation (df/dt) . For this a delay modelled as a low pass filter is included in the model and featured with a time constant (T_SISL) equal to the desired time window of the rolling average.

3.7 Power Oscillation Damping Controller

Low frequency power oscillations are inherent phenomena of AC power systems that need to be effectively damped for maintaining safe and secure operation of electricity networks. In this regard the FLUENCE BESS PPC integrates a POD (Power Oscillation Damping) controller able to regulate P and/or Q to help restore normal operation after a power oscillation is observed. The control transfer functions implemented can be seen in Figure 10 and Figure 11 where frequency and voltage are used as measurement inputs for each control branch respectively.

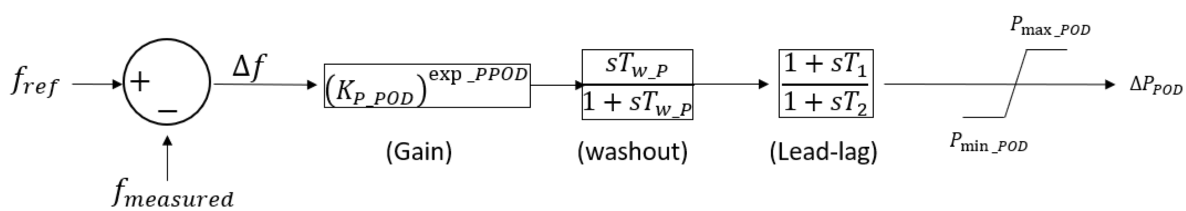

Figure 10 Active Power POD Controller

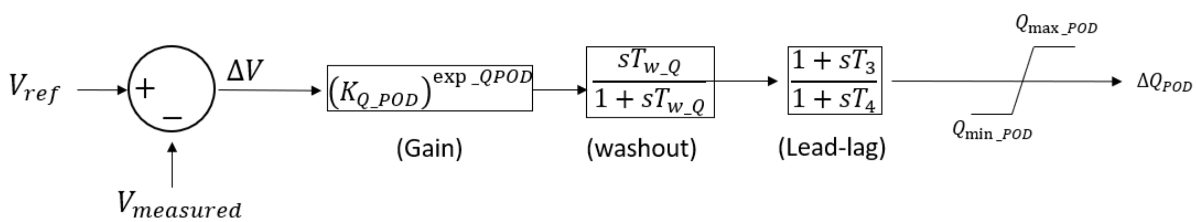

Figure 11 Reactive Power POD Controller

From the control schemes above it must be mentioned that V_{ref} and f_{ref} are fixed values initialized from the power flow results at POI of the BESS plant. Then, ΔP_{POD} is added to the remote P setpoint if PRCF=2 is activated as well as ΔQ_{POD} to the remote Q setpoint if RPCM=3.

3.8 Grid Forming Plant Controls

Fluence BESS Power Plant Controller includes additional voltage and frequency controls/commands at plant level to achieve required reactive power and active power setpoints at POI when interacting with Grid-forming or VSM based Inverters (see Figure 12).

This includes Voltage command that acts on the QREF output of the Reactive Power Controller loop and Frequency command that acts on PREF of the Active Power Controller loop.

For Grid Connected (GC) operation of the Grid forming (GFM) plant, only Voltage command is sufficient while Frequency command can be disabled. Voltage command control and Frequency command control can be enabled or disabled by changing ICON(M+19) and ICON(M+20) to 1 or 0 respectively.

The interface between Fluence PPC and the PCS (Inverter) model for VCMD and FCMD is established through ICON(M+52) and ICON (M+53) that defined the VAR numbers for Voltage reference and Frequency reference within the Inverter model.

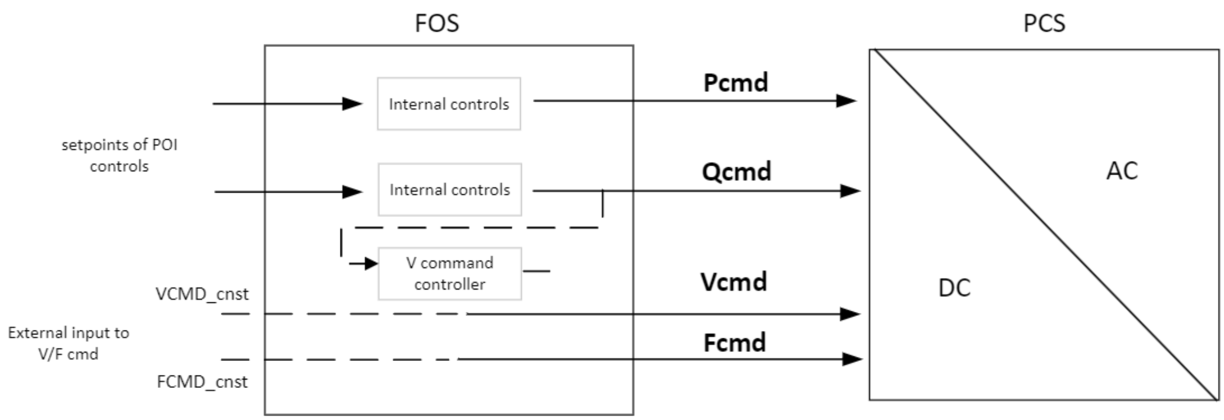

Figure 12 Fluence PPC commands to PCS/Inverter during Grid-forming operation

CON(J+113) and CON(J+114) represent the maximum limit (VCMD_MAX) and minimum limit (VCMD_MIN) of the Voltage commands. CON(J+116) and CON(J+117) represent the maximum limit (FCMD_MAX) and minimum limit (FCMD_MIN) of the Frequency commands.

3.9 PSS®E CONs, ICONs, VARs, STATEs

The PPC UDM provided may be modified to meet the needs of the user. PSS®E makes use of 4 main data arrays within the program itself to maintain constants, flags, states and internal variables. These are listed below with short descriptions of each.

- CONs: Values directly modifiable by user to tune the model
- ICONs: Control flags and bus selectors
- VARs: Variables that track the internal behavior and display outputs
- STATEs: Variables that are internal and used solely in the PSS®E interface with the model

Table 3. UDM CON Definitions

CONs	Value	Description (all P.U. values on battery MBASE unless stated otherwise)
J	1.0000	KVP - Voltage controller proportional gain
J+1	2.0000	KVI - Voltage controller integral gain
J+2	0.0200	TVM - Voltage measurement delay
J+3	0.0200	TPM - Active power measurement delay
J+4	0.0200	TQM - Reactive power measurement delay
J+5	0.5000	KPFFF - Power Factor controller feed forward gain
J+6	0.5000	TPFI- Power Factor controller integral time constant
J+7	0.5000	KQFF - Remote Q feed forward gain
J+8	2.0000	TQI - Remote Q integral time constant
J+9	0.7000	KPFF - Remote P feed forward constant
J+10	1.0000	TPI - Remote P integral time constant

J+11	0.0400	TDF - Frequency measurement delay
J+12	10.0000	PRamp_UP - Active power ramp up rate, pu/s
J+13	10.0000	PRamp_DN - Active power ramp down rate, pu/s
J+14	0.1000	KVFFSP - V-Stack remote Q feed forward gain
J+15	0.5000	TVISP - V-Stack Q integral time constant
J+16	1440.0	TSOC - Integral time constant for charging/discharging
J+17	1.05	OVDB - Over voltage deadband for stackable voltage logic
J+18	1.0500	OVV1 - Stackable voltage logic first high voltage V point
J+19	1.05	OVV2 - Stackable voltage logic second high voltage V point
J+20	1.06	OVV3 - Stackable voltage logic third high voltage V point
J+21	-0.01	OVQ1 - Stackable voltage logic first high voltage Q point
J+22	-0.02	OVQ2 - Stackable voltage logic second high voltage Q point
J+23	-0.05	OVQ3 - Stackable voltage logic third high voltage Q point
J+24	0.95	UVDB - Under voltage deadband for stackable voltage logic
J+25	0.95	UVV1 - Stackable voltage logic first low voltage V point
J+26	0.95	UVV2 - Stackable voltage logic second low voltage V point
J+27	0.94	UVV3 - Stackable voltage logic third low voltage V point
J+28	0.01	UVQ1 - Stackable voltage logic first low voltage Q point
J+29	0.02	UVQ2 - Stackable voltage logic second low voltage Q point
J+30	0.05	UVQ3 - Stackable voltage logic third low voltage Q point
J+31	50.500	OFDB - Over frequency deadband for stackable frequency logic

J+32	50.600	OFF1 - Stackable frequency logic first high frequency F point
J+33	50.700	OFF2 - Stackable frequency logic second high frequency F point
J+34	51.000	OFF3 - Stackable frequency logic third high frequency F point
J+35	-0.1000	OFP1 - Stackable frequency logic first high frequency P point
J+36	-0.2000	OFP2 - Stackable frequency logic second high frequency P point
J+37	-0.3000	OFP3 - Stackable frequency logic third high frequency P point
J+38	49.500	UFDB - Under frequency deadband for stackable frequency logic
J+39	49.400	UFF1 - Stackable frequency logic first low frequency F point
J+40	49.300	UFF2 - Stackable frequency logic second low frequency F point
J+41	49.000	UFF3 - Stackable frequency logic third low frequency F point
J+42	0.1000	UFP1 - Stackable frequency logic first low frequency P point
J+43	0.2000	UFP2 - Stackable frequency logic second low frequency P point
J+44	0.3000	UFP3 - Stackable frequency logic third low frequency P point
J+45	1.0000	QMAXINV - Maximum reactive power from inverter
J+46	-1.0000	QMININV - Minimum reactive power from inverter
J+47	1.0000	PMAXINV - Maximum active power from inverter
J+48	-1.0000	PMININV - Minimum active power from inverter
J+49	0.5300	QMAXINT - Maximum reactive power from remote Q control integrator
J+50	-0.5300	QMININT - Minimum reactive power from remote Q control integrator

J+51	0.4	PMAXINT - Maximum active power from remote P control integrator
J+52	-0.4	PMININT - Minimum active power from remote P control integrator
J+53	0.5300	QMAXPI - Maximum reactive power from Power Factor Q control PI
J+54	-0.5300	QMINPI - Minimum reactive power from Power Factor Q control PI
J+55	0.5300	QMAXPIVSP - Maximum reactive power from remote V-Stack control integrato
J+56	-0.5300	QMINPIVSP - Minimum reactive power from remote V-Stack control integrato
J+57	12.0000	SOCMIN - Minimum battery charge
J+58	98.0000	SOCMAX - Maximum battery charge
J+59	50.0000	SOCINI - Initial battery charge
J+60	0.020	TQC - Time delay for Q inverter command, sec
J+61	0.020	TPC - Time delay for P inverter command, sec
J+62	0.200	TPE - Time delay for P external inverter command
J+63	0.200	TQE - Time delay for Q external inverter command
J+64	0.850	LVRT - Low voltage threshold for PPC freeze, pu
J+65	0.050	LVRT_HYST - Low voltage hysteresis for PPC freeze (>0), pu
J+66	1.150	HVRT - High voltage threshold for PPC freeze, pu
J+67	0.050	HVRT_HYST - High voltage hysteresis for PPC freeze (>0), pu
J+68	1.0000	EXTPRJMAXP - External project P max (p.u. on external MBASE)
J+69	-1.0000	EXTPRJMINP - External project P min (p.u. on external MBASE)

J+70	1.0000	EXTPRJMAXQ - External project Q max (p.u. on external MBASE)
J+71	-1.0000	EXTPRJMINQ - External project Q min (p.u. on external MBASE)
J+72	1.0000	KQF1 - Reactive power participation factor local project
J+73	1.0000	KQF2 - Reactive power participation factor remote project
J+74	0.0200	TQ1 - Time delay for Q local inverter command (joint control), sec
J+75	0.0200	TQ2 - Time delay for Q external inverter command (joint control), sec
J+76	0.1000	Tfrzppc - Extra Time delay for PPC, sec
J+77	1.0000	VCNTR: Voltage center for droop curve, pu
J+78	0.833	PMAXPOC - Maximum active power at POC, pu
J+79	-0.833	PMINPOC - Minimum active power at POC, pu
J+80	0.274	QMAXPOC - Maximum reactive power at POC, pu
J+81	-0.274	QMINPOC - Minimum reactive power at POC, pu
J+82	0.2	PDFDTF1 - 1st Positive dFdT, Hz/s
J+83	0.5	PDFDTF2 - 2nd Positive dFdT, Hz/s
J+84	1	PDFDTF3 - 3rd Positive dFdT, Hz/s
J+85	-0.1	PDFDTP1 - 1st Power for Positive dFdT, pu
J+86	-0.2	PDFDTP2 - 2nd Power for Positive dFdT, pu
J+87	-0.3	PDFDTP3 - 3rd Power for Positive dFdT, pu
J+88	-0.2	NDFDTF1 - 1st Negative dFdT, Hz/s
J+89	-0.5	NDFDTF2 - 2nd Negative dFdT, Hz/s
J+90	-1	NDFDTF3 - 3rd Negative dFdT, Hz/s
J+91	0.1	NDFDTP1 - 1st Power for Negative dFdT, pu
J+92	0.2	NDFDTP2 - 2nd Power for Negative dFdT, pu
J+93	0.5	NDFDTP3 - 3rd Power for Negative dFdT, pu

J+94	0.08	T_SISL - SISL dFdT rolling time window (s)
J+95	0.05	T_DFDT - dFdT measurement delay (s)
J+96	10.0	TwP - P POD Washout filter time constant (s)
J+97	-0.1	POD_MINP - P POD Max. POD contribution (pu)
J+98	0.1	POD_MAXP - P POD Min. POD contribution (pu)
J+99	0.1251	T1P - P POD Lead Time Constant (s)
J+100	0.8101	T2P - P POD Lag Time Constant (s)
J+101	20	K_PODP - Q POD Gain
J+102	1	exp_PPOD – P POD Gain exponent ()
J+103	0.5	TwQ - Q POD Washout filter time constant (s)
J+104	-0.1	POD_MINQ - Q POD Max. POD contribution (pu)
J+105	0.1	POD_MAXQ - Q POD Min. POD contribution (pu)
J+106	0.1251	T1Q - Q POD Lead Time Constant (s)
J+107	0.8101	T2Q - Q POD Lag Time Constant (s)
J+108	1	K_PODQ - Q POD Gain
J+109	1	exp_QPOD – Q POD Gain exponent ()
J+110	0.05	INT_CON – Internal CON
J+111	49.5	LFDDDB - Start frequency for the LFFD function (Hz)
J+112	49.0	LFDDMIN - Minimum frequency defining the LFDD function (Hz)
J+113	1.05	VCMD_MAX- Maximum limit for the Vcmd (pu)
J+114	0.95	VCMD_MIN- Minimum limit for the Vcmd (pu)
J+115	0.3	KVCMD - Feed forward gain of the Vcmd
J+116	1.05	FCMD_MAX- Maximum limit for the Fcmd (pu)
J+117	0.95	FCMD_MIN- Minimum limit for the Fcmd (pu)
J+118	0.3	KFCMD - Feed forward gain of the Fcmd
J+119	0.02	TVC - Time delay for V inverter command, sec
J+120	0.02	TFC - Time delay for F inverter command, sec
J+121	0.08	Internal Use
J+122	100	Plant MVA Base
J+123	0.03	Internal Use

Table 4. UDM ICON Definitions

ICONs	Value	Description
M+0	1101	POI from bus number (0: Local)
M+1	1100	POI to bus number (0: Local)
M+2	1	POI circuit identifier (0: Local)
M+3	0	Reference Power to be Measured at (0: From BUS of POI, 1: To BUS of POI)
M+4	1101	Remote frequency measurement bus number (0: Local)
M+5	1100	Remote voltage measurement bus number (0: Local)
M+6	3	RPCM - Q Mode (1: Voltage, 2: PF, 3: Remote Q, 4: Local Q, 5: V-Stack
M+7	2	PRCF - P Mode (1: Local P, 2: Remote P, 3: Power Firm, 4: Local+Joint)
M+8	0	VSL - 1: Enable voltage reactive power stackable logic
M+9	0	FSL - 1: Enable frequency active power stackable logic
M+10	0	RRL - 1: Enable external reactive power controller command; 0: Disable
M+11	0	PRJPRIOR - 0: Internal project priority; 1: External project priority
M+12	0	EXTRNPRJBUS - External project machine bus (0: No external project)
M+13	1	EXTRNPRJID - External project machine ID (0: No external project)
M+14	0	EXTRNLPRJTP- External project type (0: Disabled, 1: PE, 2: SMA)
M+15	0	SISL - 1: Enable Synthetic inertia power stackable logic
M+16	0	DM - Discontinuous Mode for SI Enable = 1, Disable =0
M+17	0	PPOD_ON - P POD Enable = 1, Disable =0
M+18	0	QPOD_ON - Q POD Enable = 1, Disable =0
M+19	0	LFDD - Low Frequency Demand Disconnection Enable = 1, Disable =0
M+20	1	VCMD_EN - GFM control Enable=1, Disable=0
M+21	0	FCMD_EN - Fcmd control Enable=1, Disable=0
M+22	1110	Local Gen. 1 Bus Number
M+23	1111	Local Gen. 2 Bus Number

M+24	1112	Local Gen. 3 Bus Number
M+25	1113	Local Gen. 4 Bus Number
M+26	0	Local Gen. 5 Bus Number
M+27	0	Local Gen. 6 Bus Number
M+28	0	Local Gen. 7 Bus Number
M+29	0	Local Gen. 8 Bus Number
M+30	0	Local Gen. 9 Bus Number
M+31	0	Local Gen. 10 Bus Number
M+32	0	Local Gen. 11 Bus Number
M+33	0	Local Gen. 12 Bus Number
M+34	0	Local Gen. 13 Bus Number
M+35	0	Local Gen. 14 Bus Number
M+36	0	Local Gen. 15 Bus Number
M+37	0	Local Gen. 16 Bus Number
M+38	0	Local Gen. 17 Bus Number
M+39	0	Local Gen. 18 Bus Number
M+40	0	Local Gen. 19 Bus Number
M+41	0	Local Gen. 20 Bus Number
M+42	0	Local Gen. 21 Bus Number
M+43	0	Local Gen. 22 Bus Number
M+44	0	Local Gen. 23 Bus Number
M+45	0	Local Gen. 24 Bus Number
M+46	0	Local Gen. 25 Bus Number
M+47	0	Local Gen. 26 Bus Number
M+48	0	Local Gen. 27 Bus Number
M+49	0	Local Gen. 28 Bus Number
M+50	0	Local Gen. 29 Bus Number
M+51	0	Local Gen. 30 Bus Number
M+52	9999	Gen. VAR Number for the P command 9999 : Internal WPCMND / XADIFD

M+53	9999	Gen. VAR Number for the Q command 9999 : Internal WQCMND / EFD
M+54	0	Gen. VAR Number for the V command 9999 : Internal VREF
M+55	1	Gen. VAR Number for the F command
M+56	0	Remote voltage measurement bus number for FRT (0: ICON(M+4) is used)
M+57	1	IBR_INT (Inverter Interface - Default = 1: WELEC, 2: WGEN)
M+58	2	INV_MODEL (Machine Type 1: Conventional, 2: Wind Machine)
M+59	1	Internal - Default = 1, Else = 0

Table 5. UDM VAR Definitions

VARs	Value	Description
L		PRMTCMD – Remote active power command (MW)
L+1		QRMTCMD – Remote reactive power command (MVAR)
L+2		PLCLCMD – Local active power command (MW)
L+3		QLCLCMD – Local reactive power command (MVAR)
L+4		PRMTMEAS – Active power measurement at POI
L+5		QRMTMEAS – Reactive power measurement at POI
L+6		VCMD – Voltage command
L+7		PFCMD – Power factor command
L+8		PREFINT – Output active power reference to battery PSSE WPCMND array
L+9		QREFINT – Output reactive power reference to battery PSSE WQCMND array
L+10		SOC – State of charge for the battery
L+11		PRMTFRMCMD – Remote branch for joint firming (MW)
L+12		PLCLCMDEXT – Local active power command for external project (MW)
L+13		QLCLCMDEXT – Local reactive power command for external project (MVAR)

L+14		PREFEXT – Output active power reference to external project PSSE WPCMND array
L+15		QREFEXT – Output reactive power reference to external project PSSE WQCMND array
L+16		Internal variable
L+17		Internal variable
L+18		VSET – Voltage set point for RPCM = 5
L+19		VCNTR – Voltage droop center for RPCM = 5
L+20		Internal variable
L+21		HVRT_FLAG – Status of HVRT mode
L+33		LVRT_FLAG – Status of LVRT mode
L+22 – L+43		Internal variable, except for VAR(L+33)
L+44		FRZ_FLAG – PPC freeze flag with 'Tfrzppc' delay
L+45 - L+51		Internal variables
L+52		VCMD_EXT – Voltage command PPC-PCS (pu)
L+53		VCMD_CNST – Constant Voltage command offset (pu)
L+54		FCMD_EXT - Frequency command PPC-PCS (Hz)
L+55		FCMD_CNST - Constant Frequency command offset (pu)
L+56		VMEASD_FRT – FRT Bus Voltage measurement
L+57 – L+247		Internal variables

Table 6. UDM STATE Definitions

STATEs	Value	Description
K		Project or remote voltage measurement
K+1		Voltage controller PI state
K+2		Project or POI delayed active power measurement
K+3		Project or POI delayed reactive power measurement
K+4		Power factor controller integrator state
K+5		Remote reactive power command logic integrator state
K+6		Remote active power command logic integrator state
K+7		Project or remote frequency measurement
K+8		Charging integrator state
K+9		Delayed active power command - battery
K+10		Delayed reactive power command - battery
K+11		Delayed active power command – external project
K+12		Delayed reactive power command – external project
K+13		Delayed reactive power command – battery; Join logic
K+14		Delayed reactive power command – external project; Join logic
K+15		RPCM = 5 Integrator state
K+16		Delayed frequency measurement for DFDT calculation
K+17		P POD washout filter state
K+18		P POD lead-lag filter state
K+19		Q POD washout filter state
K+20		Q POD lead-lag filter state
K+21		DFDT delayed value
K+22		FRT Bus Voltage measurement

3.10 Dynamic File

The dynamic data associated with the Fluence BESS PPC UDM is stored in the PSS®E DYR file format and is shown as follows:

BUSID ’USRBUS’ ’model name’ IC IT NI NC NS NV data list /

The BUSID will represent the bus number in which our project is located and the PPC is conencted. USRBUS is the generic term for a UDM PSS®E “other” type user-written models and should not be modified. ‘model name’ represents the name of the model developed. The name of the UDM in this case is ‘FLNCPPC_V1020.’ The next 6 entries IC, IT, NI, NC, NS, NV should not be modified as they represent the type of model along with number of internal array entries. Finally, the data list will include the list of ICONs and CONs respectively. The DYR file for this particular UDM will be written as follows:

IBUS 'USRBUS' 'FLNPPC_ V1020' 504 0 60 124 23 248 M M+1 M+2 … M+59 J J+1 J+2 … J+123 /

4. Generic Model Representation

In order to fulfill requests for a generic model (GM) representation of the Fluence BESS PPC by Utilities and Independent Service Operators (ISO), EPE has prepared a GM to represent the UDM for the applicable control modes. The GM is limited in its active power and voltage control capabilities as it is meant to represent the majority of PPCs used worldwide. The voltage control modes from the UDM that are representable in the GM are denoted in Table 7 and Figure 13. For all voltage control modes to be simulated with the GM, the UDM will need to have the ICONs set as stated in Table 7, along with any PI gain adjustments to match the GM control logic.

Table 7. UDM Voltage Control Modes Represented in the GM

Control Mode	Description	ICON Setting
Voltage Control	Remote voltage control	RPCM = 1/5 RRL = 0 VSL = 1 (RPCM = 5)
Reactive Power Control	Remote reactive power control (Feedforward disabled KQFF = 0)	RPCM = 3 VSL = 0/1 RRL = 0

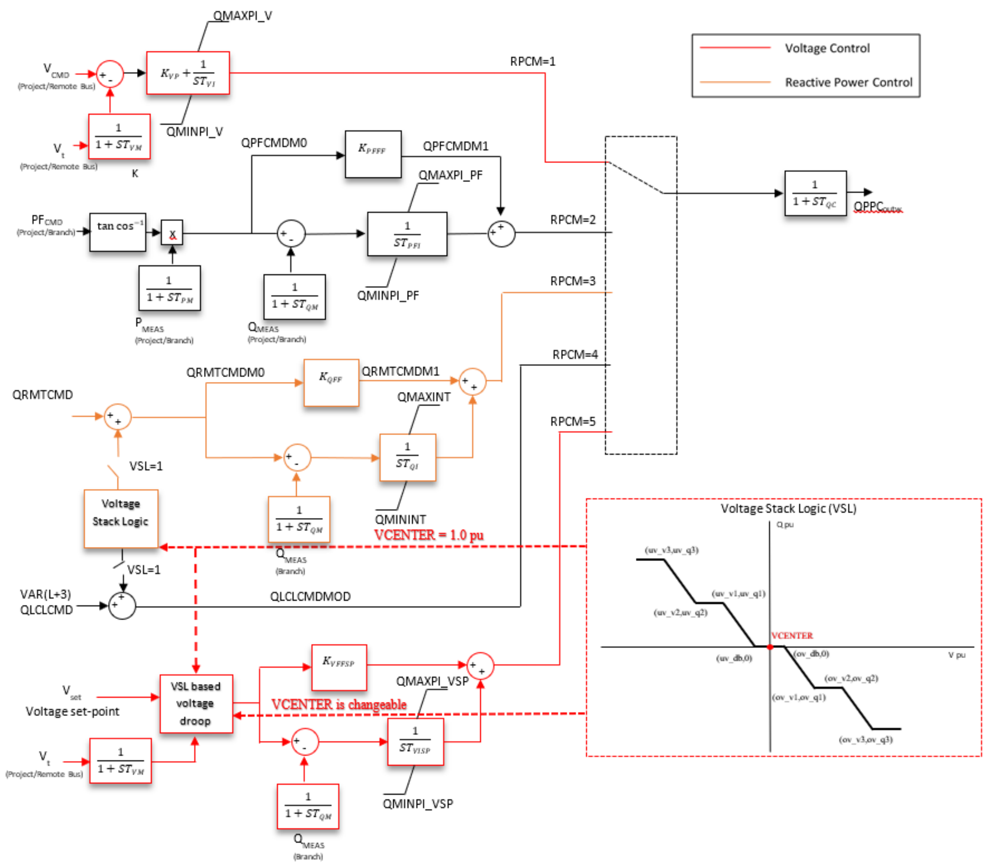

Figure 13. UDM Voltage Control Modes Represented in the GM

The active power control modes from the UDM that are representable in the GM are denoted in Table 8 and Figure 14. For all active power control modes to be simulated with the GM, the UDM will need to have the ICONs set as stated in Table 8, along with any PI gain adjustments to match the GM control logic.

Table 8. UDM Active Power Control Modes Represented in the GM

Control Mode	Description	ICON Setting
Frequency Control	Remote frequency control (Feedforward disabled KPFF = 0)	PRCF = 2 FSL = 1
Active Power Control	Remote active power control (Feedforward disabled KPFF = 0)	PRCF = 2 FSL = 0

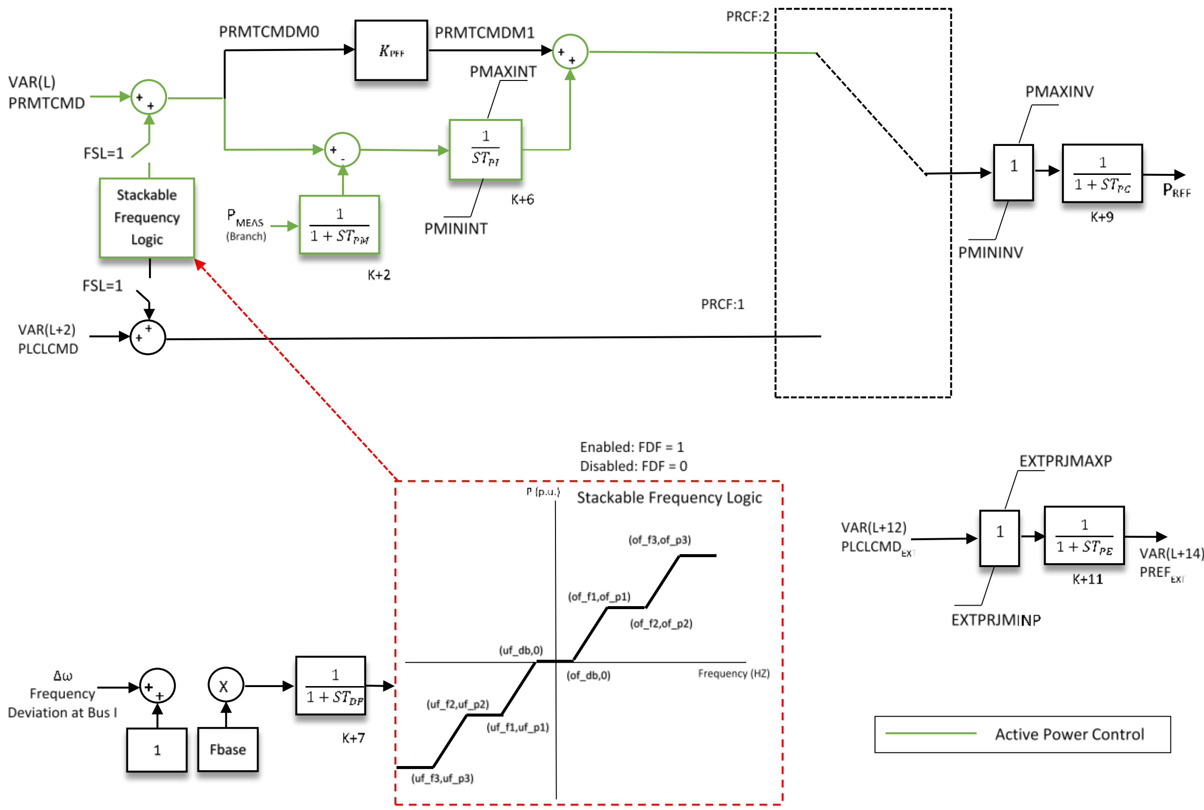

Figure 14. UDM Voltage Control Modes Represented in the GM

The provided PPC GM may be modified to meet the needs of the user. A mapping of key variables from the UDM to the GM are shown in Table 9 and Table 10. The variable name "DNE" means that the variable doesn't exist in the UDM. For some control modes the same variable is used and for others it needs to be removed; all variable options for each GM variable are shown in the tables below. The DYR file for the GM will be written as follows:

IBUS 'USRMDL' IM 'REPCAU1' 107 0 7 27 7 9 M M+1 M+2 ... M+6 J J+1 J+2 ... J+26 /

Table 9. GM CON Definitions

CON	Value	Description	UDM Variable
J	0.02	Tfltr, Voltage or reactive power measurement filter time constant (s)	TVM, TQM
J+1	1	Kp, Reactive power PI control proportional gain (pu)	KVP, DNE
J+2	0.5	Ki, Reactive power PI control integral gain (pu)	KVI, 1/TQI
J+3	0	Tft, Lead time constant (s)	DNE
J+4	0.02	Tfv, Lag time constant (s)	TQC
J+5	0	Vfrz, Voltage below which State s2 is frozen (pu)	DNE
J+6	0	Rc, Line drop compensation resistance (pu)	DNE
J+7	0	Xc, Line drop compensation reactance (pu)	DNE
J+8	0	Kc, Reactive current compensation gain (pu)	Slope of Voltage Stack Logic
J+9	9999	emax, upper limit on deadband output (pu)	DNE
J+10	-9999	emin, lower limit on deadband output (pu)	DNE
J+11	0	dbd1, lower threshold for reactive power control deadband (<=0)	DNE
J+12	0	dbd2, upper threshold for reactive power control deadband (>=0)	DNE
J+13	1	Qmax, Upper limit on output of V/Q control (pu)	QMAXPI, QMAXINT
J+14	-1	Qmin, Lower limit on output of V/Q control (pu)	QMINPI, QMININT
J+15	0	Kpg, Proportional gain for power control (pu)	DNE
J+16	1	Kig, Proportional gain for power control (pu)	TPI
J+17	0.02	Tp, Real power measurement filter time constant (s)	TPM
J+18	-0.00833	fdbd1, Deadband for frequency control, lower threshold (<=0)	UFDB in pu

J+19	0.00833	fdbd2, Deadband for frequency control, upper threshold (>=0)	OFDB in pu
J+20	9999	femax, frequency error upper limit (pu)	DNE
J+21	9999	femin, frequency error lower limit (pu)	DNE
J+22	0.2	Pmax, upper limit on power reference (pu)	PMAXINT, PMAXINV
J+23	-0.2	Pmin, lower limit on power reference (pu)	PMININT, PMININV
J+24	0.02	Tg, Power Controller lag time constant (s)	TPC
J+25	100	Ddn, droop for over-frequency conditions (pu)	Slope of Frequency Stack Logic
J+26	100	Dup, droop for under-frequency conditions (pu)	Slope of Frequency Stack Logic

Table 10. GM ICON Definitions

ICON	Value	Description	UDM Variable
M	0	Remote bus number or 0 for local voltage control	Remote voltage measurement
M+1	0	Monitored branch FROM bus	POI From Bus
M+2	0	Monitored branch TO bus	POI To Bus
M+3	'1'	Monitored branch ID (enter within single quotes)	DNE
M+4	0 or 1	VCFlag, droop flag (0: with droop,1: line drop compensation)	RPCM, VSL
M+5	1	RefFlag, flag for V or Q control(0: Q control, 1: V control)	RPCM, VSL
M+6	1	Fflag, 0: disable frequency control, 1: enable	PRCF, FSL

5. Case Study

Testing of the developed PPC model leverages a single machine infinite bus network. The infinite bus network models a stiff system to aid in demonstration. The one line is shown in Figure 15. The battery is represented by a machine located at bus 1111 and an external solar project is represented at bus 1112. For dynamics, the developed model represents the PPC, while the generator and control models for both the battery and solar are represented by Power Electronics'[6] dynamic models 'PE_GEN_P1000a' and 'PE_CONT_P1000a' respectively. The parameters used for the Power Electronics' models can be found in Appendix A. The Power Electronics control model was set to allow large ramp rates as well as disable voltage dip control. The protection within the generator model was disabled. Several tests were performed to validate the model. Table 11 shows the representative grid generator parameters and Table 12 and Table 13 shows the parameters for the BESS and solar generators where our dynamics models are attached.

Figure 15. Single Machine Infinite Bus

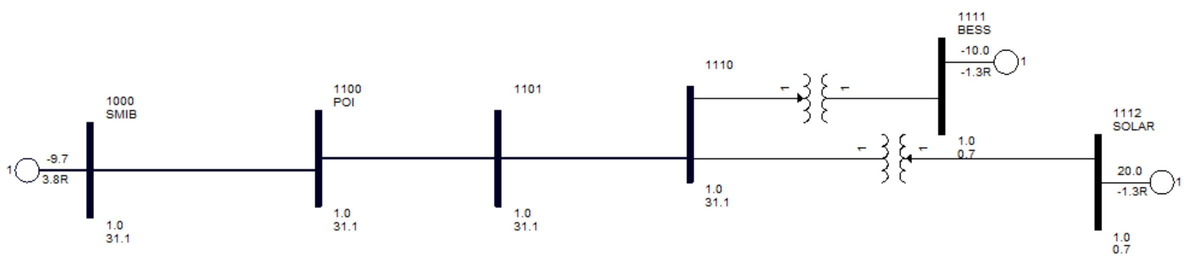

Table 11. Infinite Bus Generator Variables

Parameter	Value	Unit
P_{max}	9999	MW
P_{min}	-9999	MW
Q_{max}	9999	MVAr
Q_{min}	-9999	MVAr
Mbase	100	MVA
R Source	0.0	per unit on Generator base
X Source	0.010	per unit on Generator base

[6] Power Electronics PE_PSSE_PCSK_P1000a_R01

Table 12. BESS Generator Variables

Parameter	Value	Unit
P_{max}	30	MW
P_{min}	-30	MW
Q_{max}	15	MVAr
Q_{min}	-15	MVAr
Mbase	35	MVA
R Source	99999.0	per unit on Generator base
X Source	99999.0	per unit on Generator base

Table 13. Solar Generator Variables

Parameter	Value	Unit
P_{max}	245	MW
P_{min}	0	MW
Q_{max}	50	MVAr
Q_{min}	-50	MVAr
Mbase	245	MVA
R Source	99999.0	per unit on Generator base
X Source	99999.0	per unit on Generator base

EPE performed tests for every available control option within the developed PPC. These include:

- Local/Remote Active Power Manual Dispatch (Battery)
- Local/Remote Reactive Power Manual Dispatch (Battery)
- Local/Remote Power Factor Control
- Local/Remote Voltage Control
- Voltage Droop Logic
- Frequency Droop Logic

- Local Active Power Manual Dispatch (External Project)
- Local Reactive Power Manual Dispatch (External Project)
- Joint Project Reactive Power Control for Remote Voltage Control
- Active Power Firming

5.1 Local Battery Active Power Manual Dispatch

The active power of the BESS may be controlled by setting PRCF to 1 and modifying VAR (L+2). Figure 16 shows the local active power command. The active power response of the BESS is shown in Figure 17.

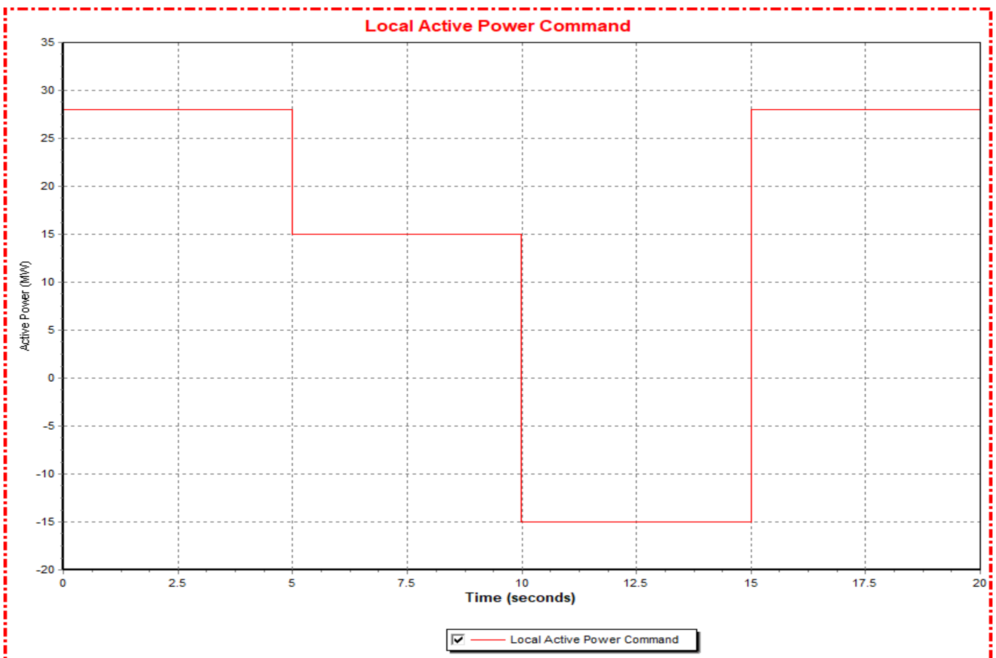

Figure 16. Local Active Power Command

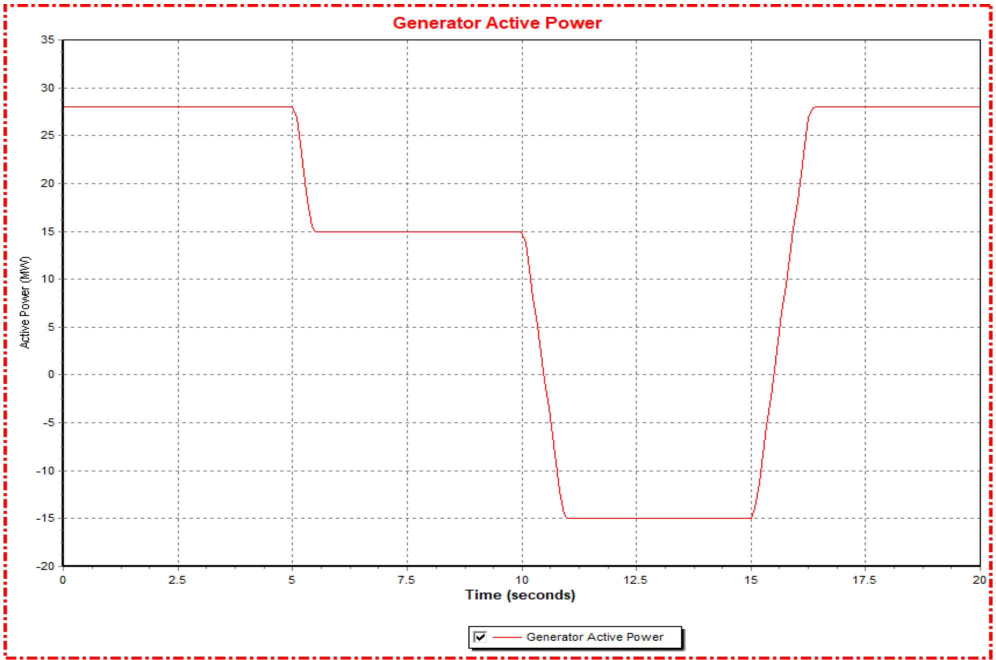

Figure 17. Generator Active Power

5.1 Local Battery Reactive Power Manual Dispatch

The local reactive power of the BESS may be controlled by setting RPCM to 1 and modifying VAR (L+3). Figure 18 shows the local reactive power command. The reactive power response of the BESS is shown in Figure 19.

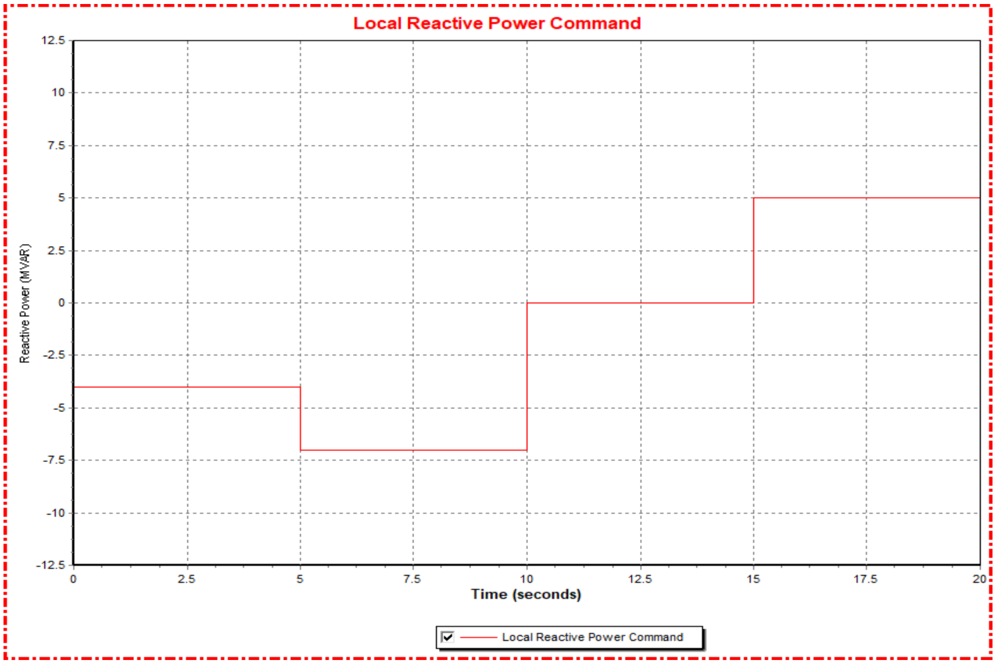

Figure 18. Local Reactive Power Command

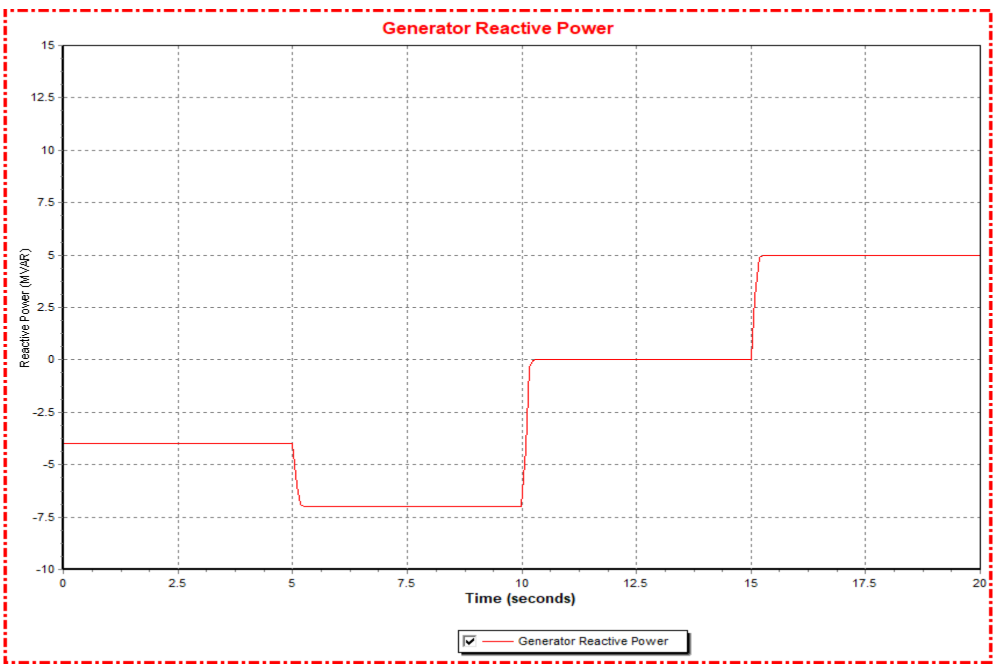

Figure 19. Generator Reactive Power

5.2 Remote Active Power Manual Dispatch

The remote active power of a branch, specified via ICON (M) through ICON (M+2), may be controlled by setting PRCF to 2 and modifying VAR (L). Figure 20 shows the remote active power command at the controlled branch. The active power response of the BESS is shown in Figure 21.

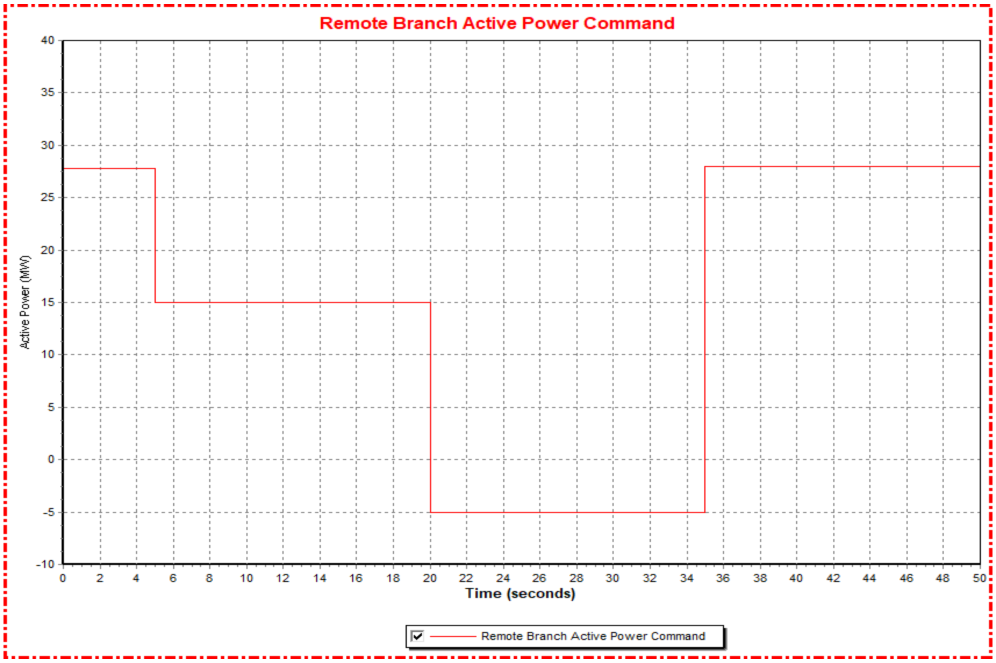

Figure 20. Remote Branch Active Power Command

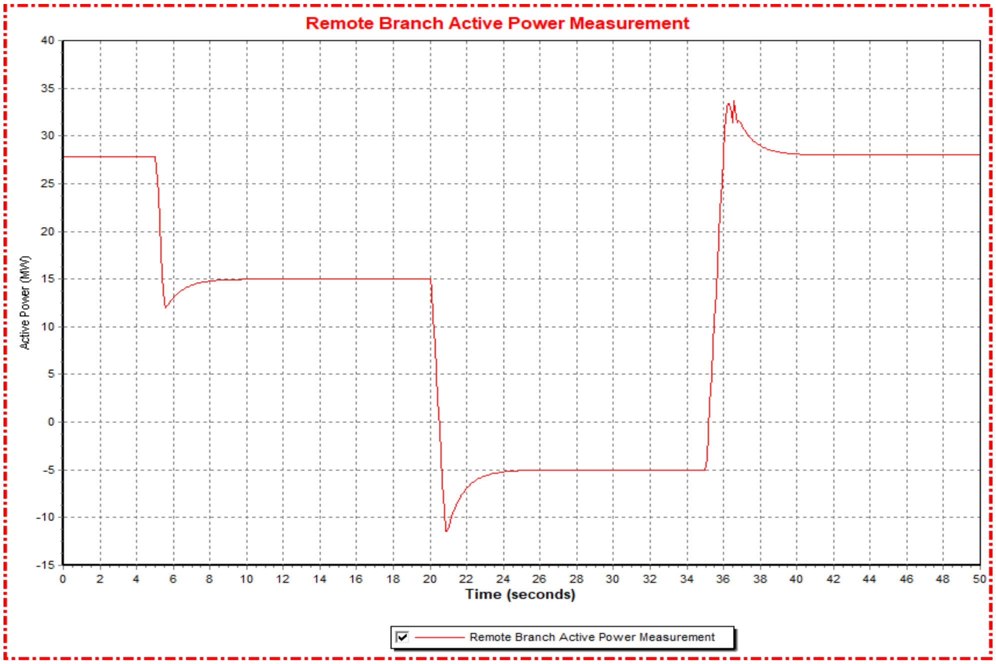

Figure 21. Remote Branch Active Power Measurement

5.1 Remote Reactive Power Manual Dispatch

The remote reactive power of a branch, specified via ICON (M) through ICON (M+2), may be controlled by setting RPCM to 3 and modifying VAR (L+1). Figure 22 shows the remote reactive power command at the controlled branch. The reactive power response of the BESS is shown in Figure 23.

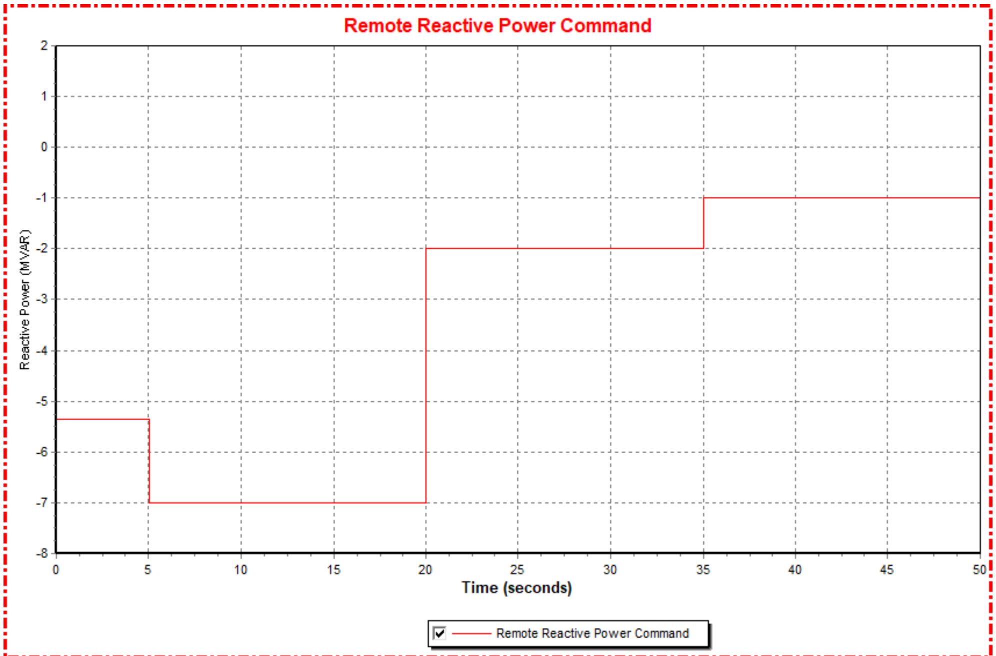

Figure 22. Remote Reactive Power Command

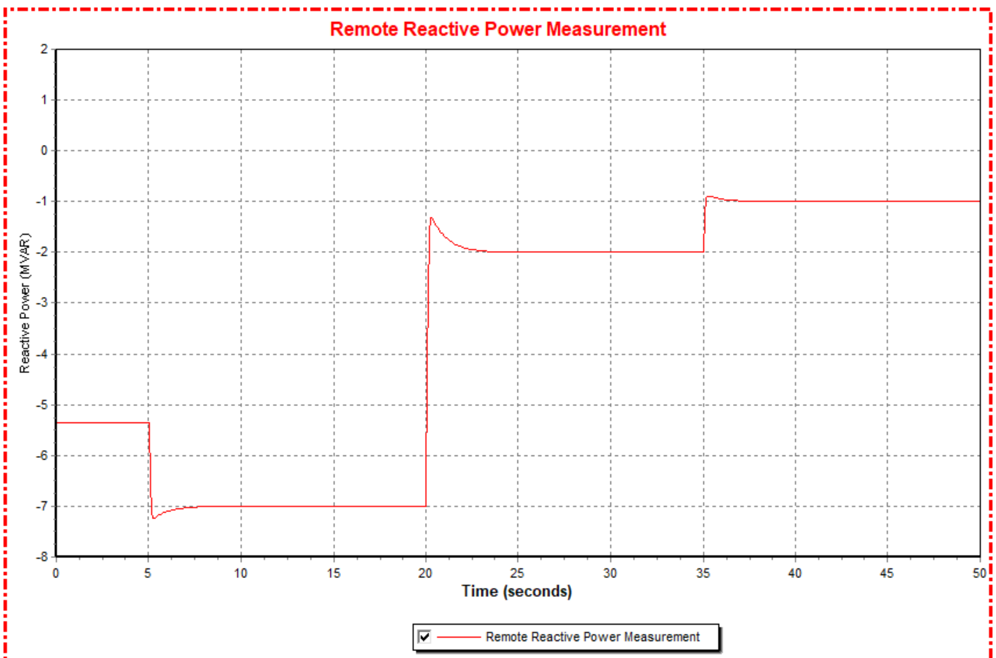

Figure 23. Remote Reactive Power Measurement

5.2 Local External Project Active Power Control

The local active power of an external project may be enabled in two main ways. Setting PRCF to 1 or 2 allows a direct pass through of the command to the external project with no changes. Setting PRCF to 3 or 4 allow the external project active power to be modified based on droop logic and/or firming logic. We address this in a separate test and focus on PRCF being set to 1. The external project is specified via its bus number and ID with ICON (M+11) and ICON (M+12). Figure 24 shows the remote active power command at the external project. The user may specify ICON (M+13) to 1 when controlling a Power Electronics project or ICON (M+13) to 2 when controlling an SMA project. The active power response when controlling a Power Electronics project is shown in Figure 25 whereas the response when controlling an SMA project is shown in Figure 26.

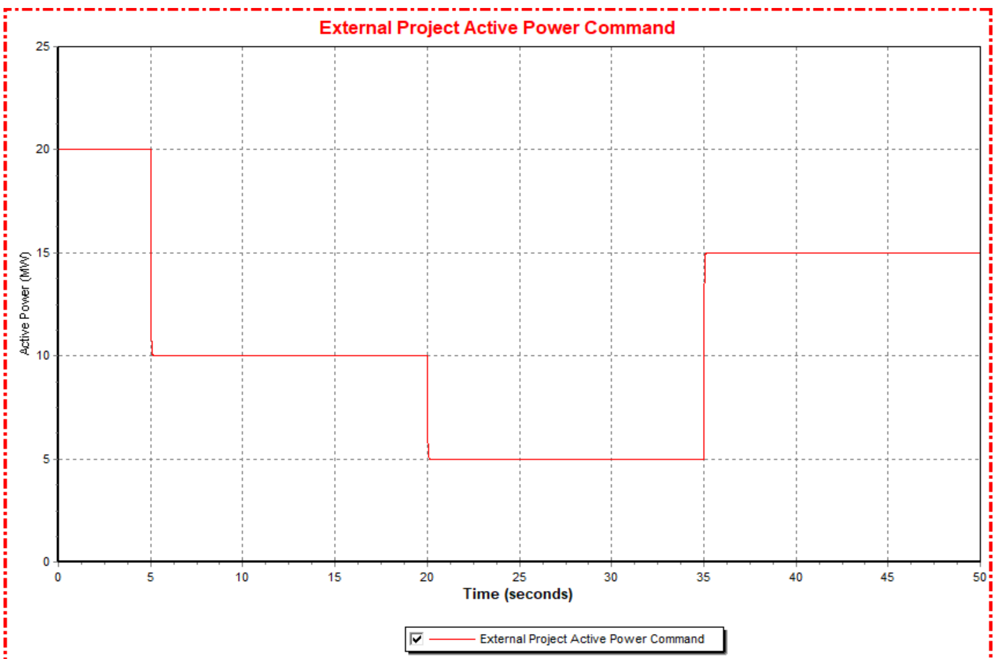

Figure 24. External Project Active Power Command

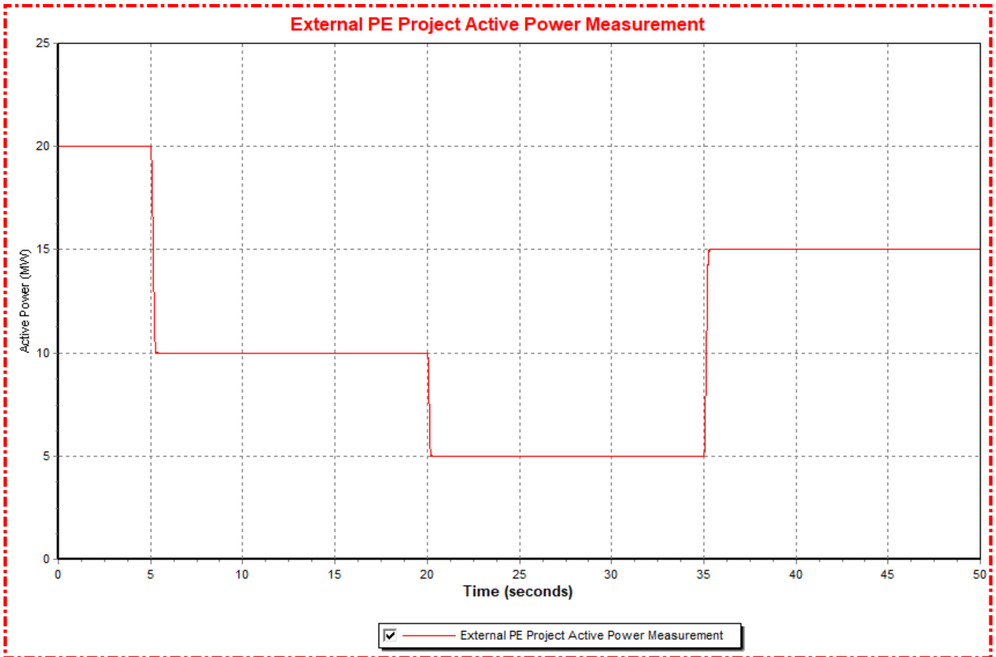

Figure 25. Power Electronics Project Active Power Measurement

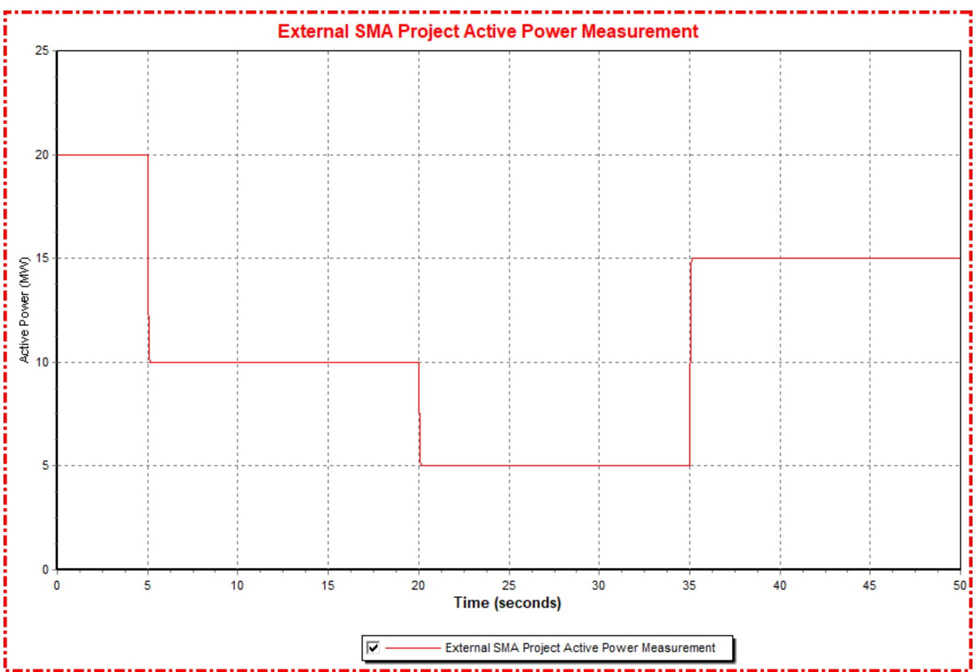

Figure 26. SMA Project Active Power Measurement

5.3 Local External Project Reactive Power Control

The local reactive power of an external project may be enabled in two main ways. Setting RRL to 1 will allow the external project's reactive power command to be supplemented by the PPC reactive power control logic. In this case, we focus on setting RRL to 0 which will directly pass the external project's reactive power control to the external project's external reactive power reference. The external project is specified via its bus number and ID with ICON (M+11) and ICON (M+12). Figure 27 shows the remote reactive power command at the external project. The user may specify ICON (M+13) to 1 when controlling a Power Electronics project or ICON (M+13) to 2 when controlling an SMA project. The reactive power response when controlling a Power Electronics project is shown in Figure 28 whereas the response when controlling an SMA project is shown in Figure 29.

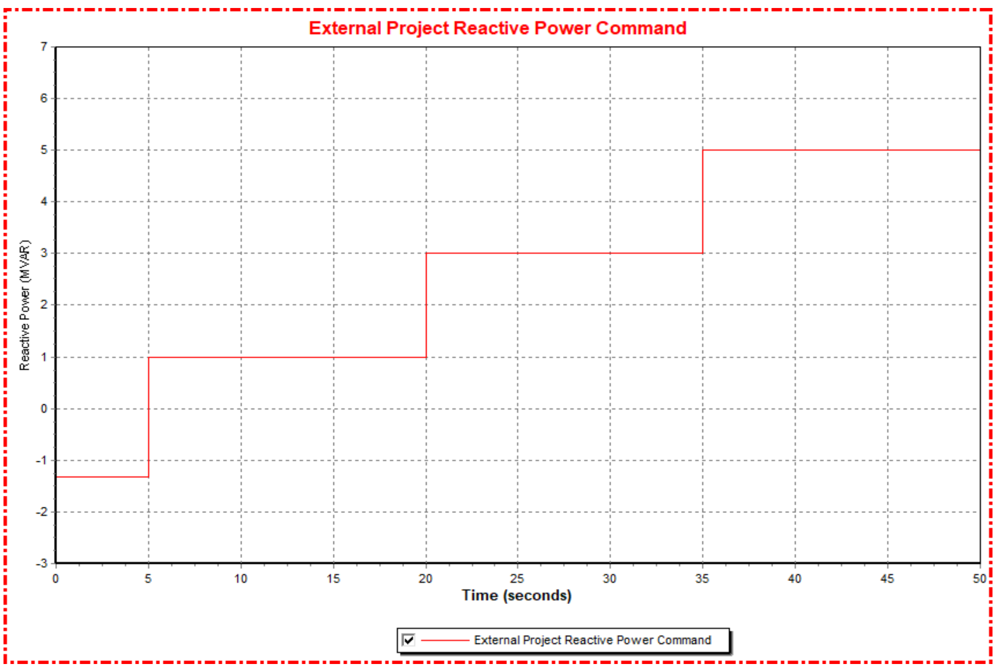

Figure 27. External Project Reactive Power Command

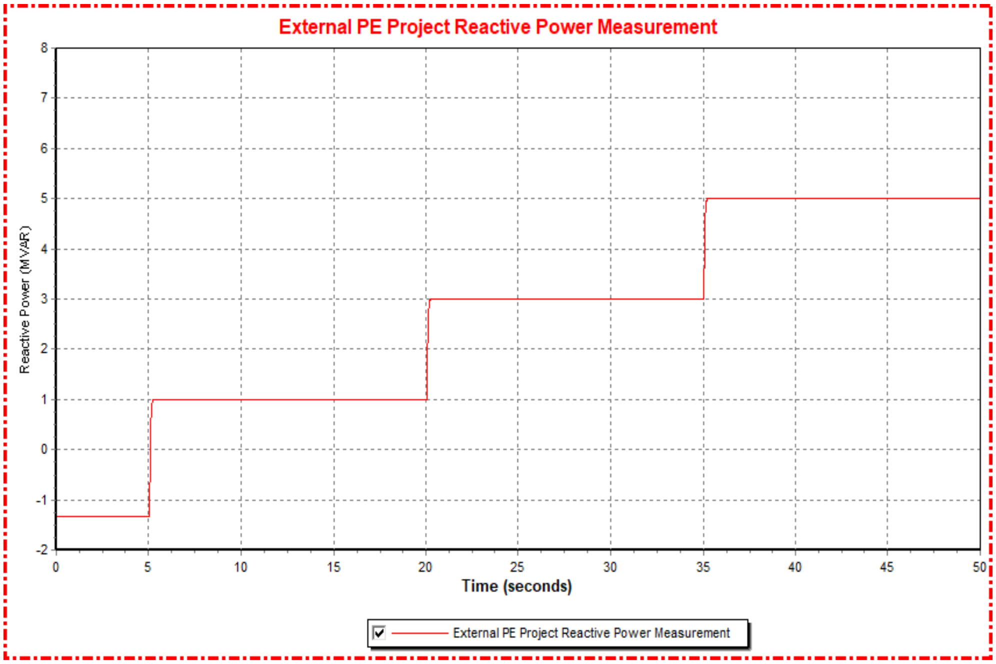

Figure 28. Power Electronics Project Reactive Power Measurement

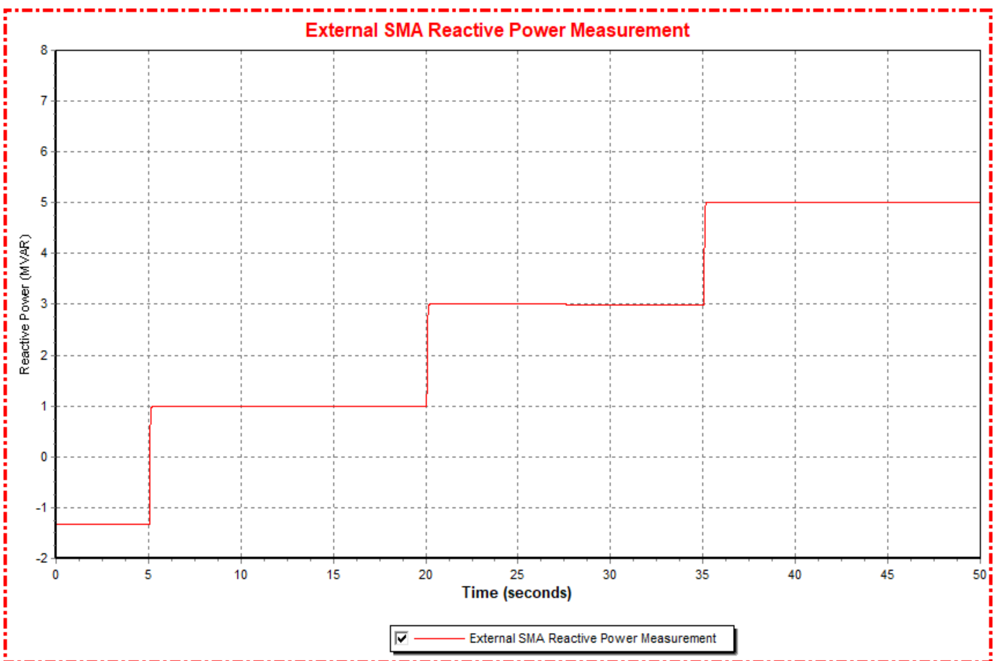

Figure 29. SMA Reactive Power Measurement

5.4 Local Power Factor Control

Power factor control may be enabled by setting RPCM to 2 and modifying VAR (L+7). For local power factor control, the user must set ICON (M) through ICON (M+2) to 0s. We assume the battery provides all reactive support by setting RRL to 0. A power factor command of 0.97 leading is imposed at 5 seconds. Figure 30 shows the active power of the BESS. Figure 31 shows the reactive power of the BESS.

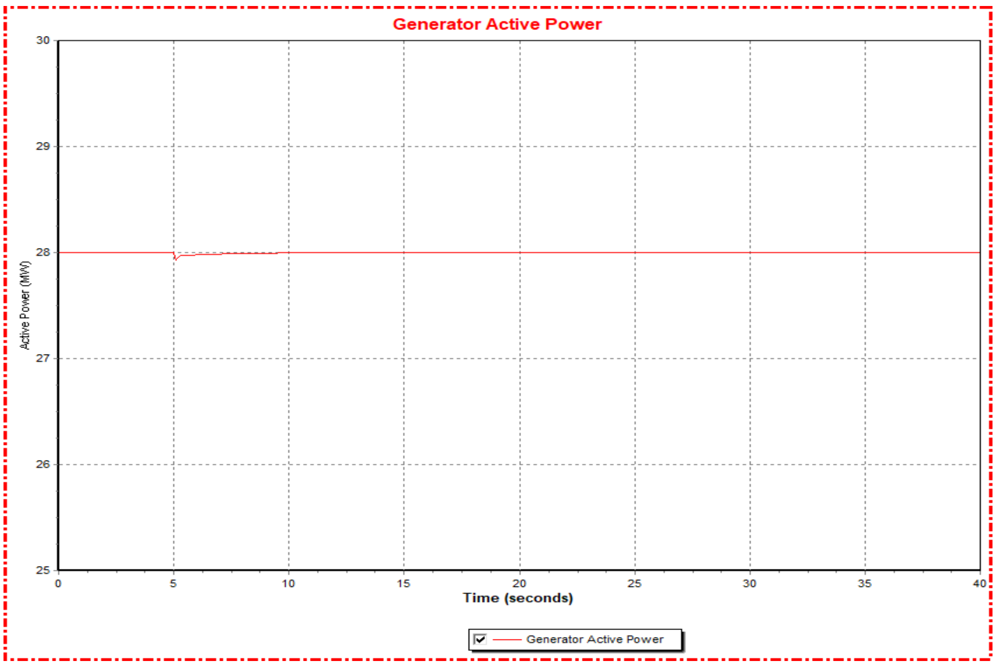

Figure 30. Generator Active Power

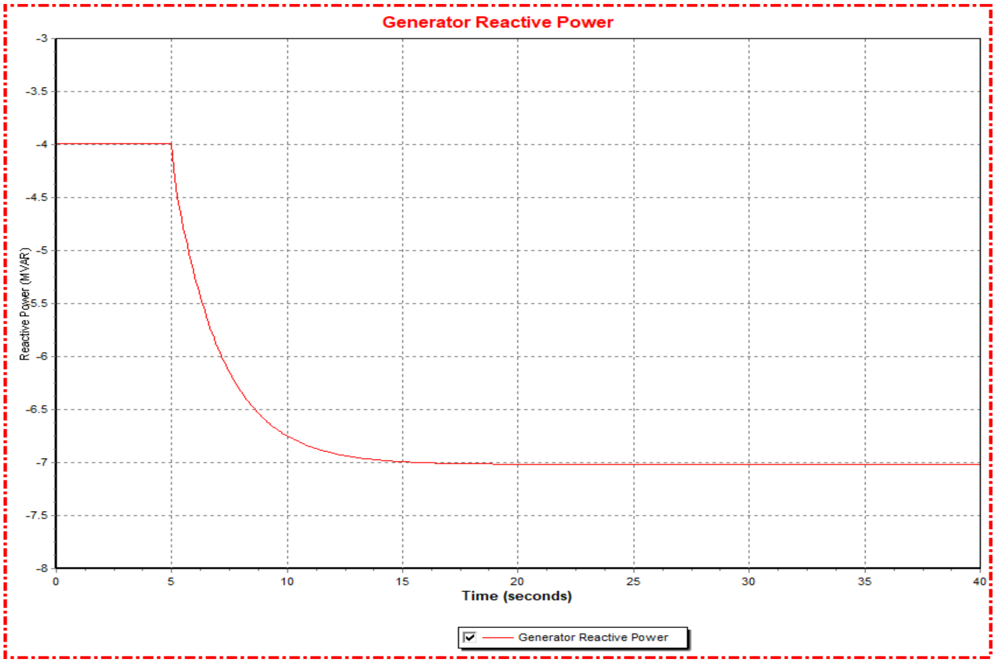

Figure 31. Generator Reactive Power

5.5 Remote Power Factor Control

Power factor control may be enabled by setting RPCM to 2 and modifying VAR (L+7). For remote power factor control, the user may set ICON (M) through ICON (M+2) to the branch of control. In this case, we control the POI branch. A power factor command of 0.97 leading is imposed at 5 seconds. We assume the battery provides all reactive support by setting RRL to 0. Figure 32 shows the branch active power. Figure 33 shows the branch reactive power.

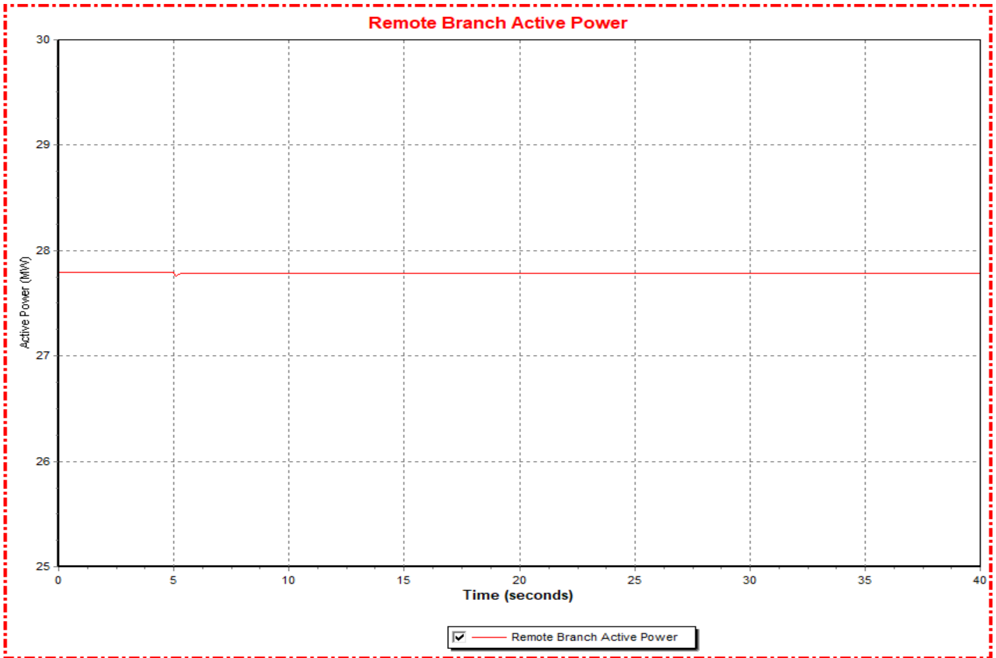

Figure 32. Remote Branch Active Power

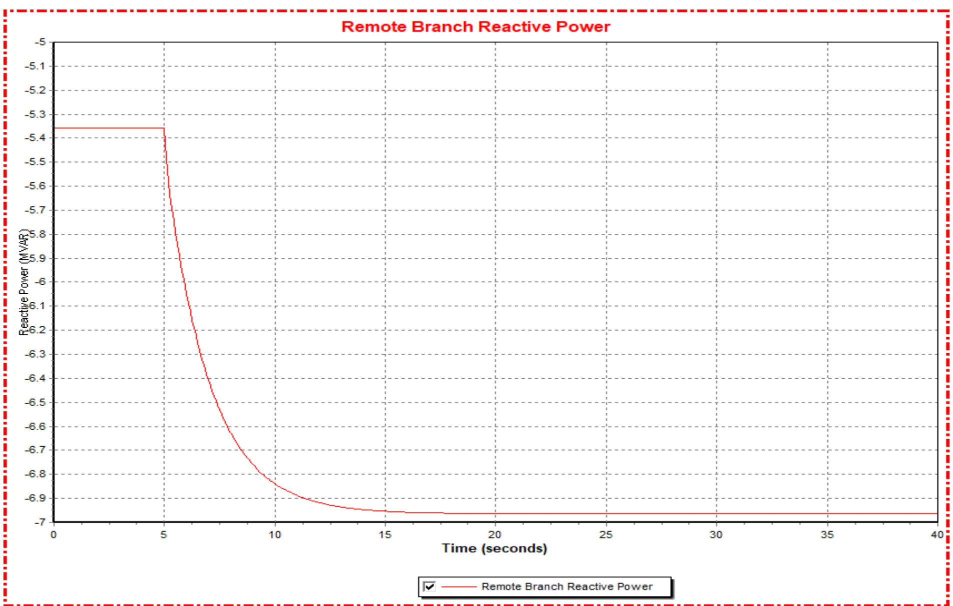

Figure 33. Remote Branch Reactive Power

5.6 Local Voltage Control

Local voltage control may be enabled by setting RPCM to 1 and modifying VAR (L+6). ICON (M+4) must be set to the bus point of control, in this case 0 for local. A voltage command of 0.95 p.u. is imposed at 5 seconds. We assume the battery provides all reactive support by setting RRL to 0. Figure 34 shows the reactive power of the BESS and Figure 35 shows the voltage at the local bus.

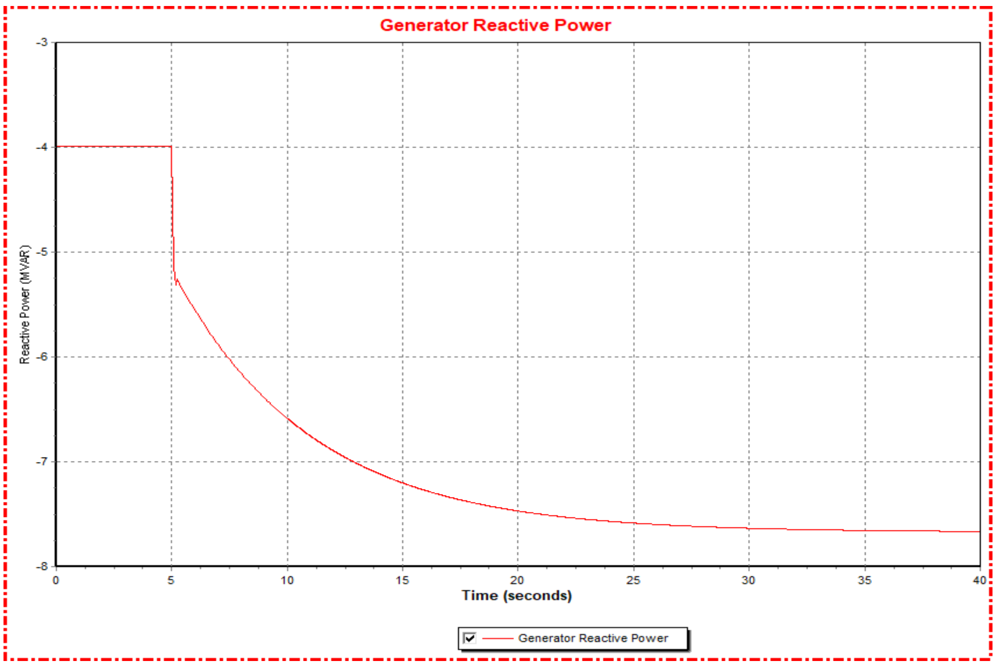

Figure 34. Generator Reactive Power

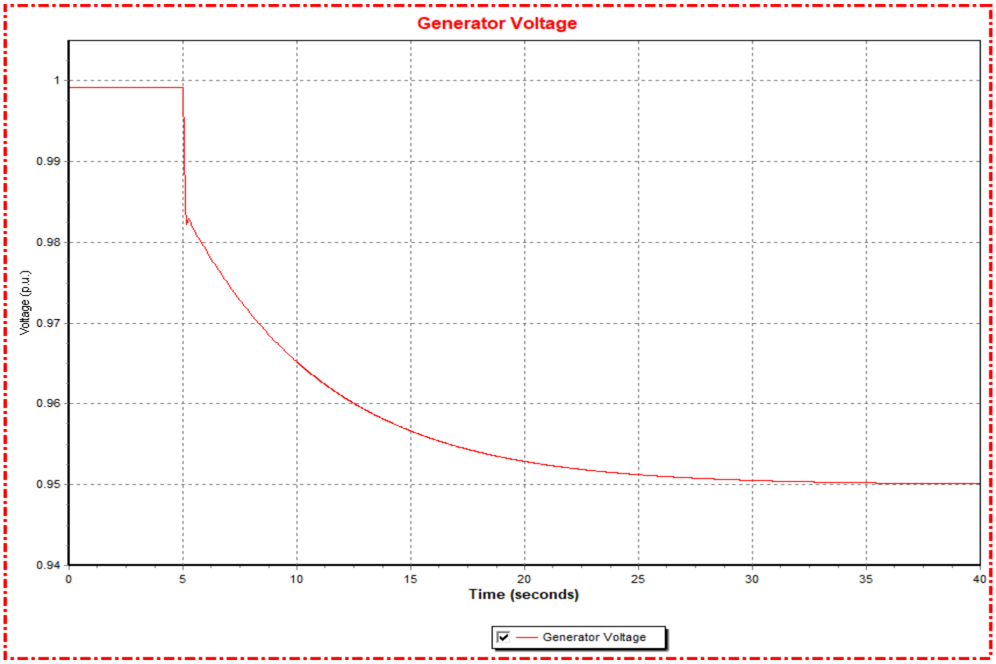

Figure 35. Generator Voltage

5.7 Remote Voltage Control

Remote voltage control may be enabled by setting RPCM to 1 and modifying VAR (L+6). ICON (M+4) must be set to the bus point of control, in this case the POI bus 1100. A voltage command of 0.95 p.u. is imposed at 5 seconds. We assume the battery provides all reactive support by setting RRL to 0. Figure 36 shows the voltage at the local bus and Figure 37 shows the reactive power of the BESS.

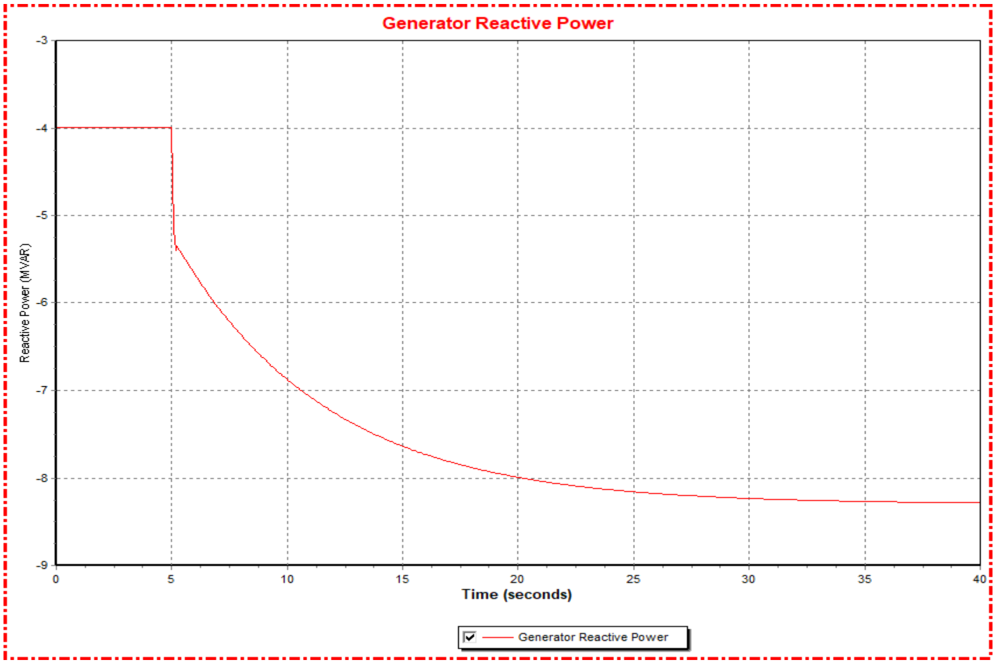

Figure 36. Generator Reactive Power

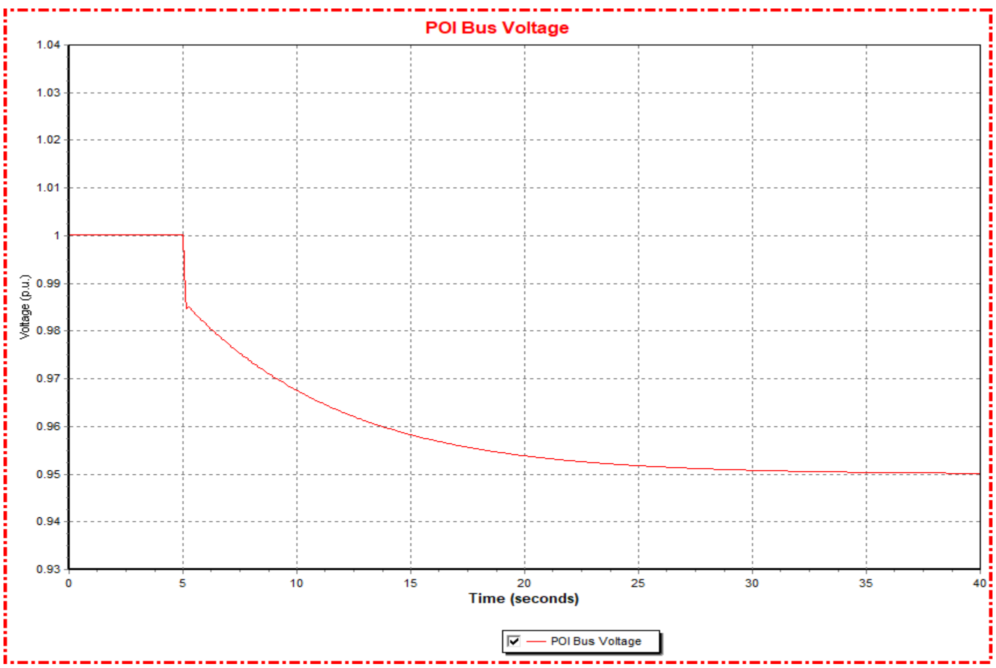

Figure 37. POI Bus Voltage

5.8 Remote Voltage Control – Joint

We perform an additional voltage control test to display the battery and external project models working together to control a voltage based on their associated participation factors. Remote voltage control may be enabled by setting RPCM to 1 and modifying VAR (L+6). ICON (M+4) must be set to the bus point of control, in this case the POI bus 1100. A voltage command of 0.98 p.u. is imposed at 5 seconds. We assume participation factors of 0.8 for the battery and 0.2 for the external project. Figure 38, Figure 39, and Figure 40 show the POI voltage, external project reactive power, and battery reactive power respectively. One may observe the results of the test in Table 14. Similar to previous tests, the user may specify commanding an external PE or SMA project by setting ICON (M+13) to 1 or 2 respectively.

Table 14. Reactive Power Participation

	Start Q (MVAr)	End Q (MVAr)	Difference (MVAr)	Additional Contribution (%)
Battery	0.0668	-1.06	-1.122	80
External Project	0.0669	-0.214	-0.281	20
Total	0.1337	-1.27	-1.403	100

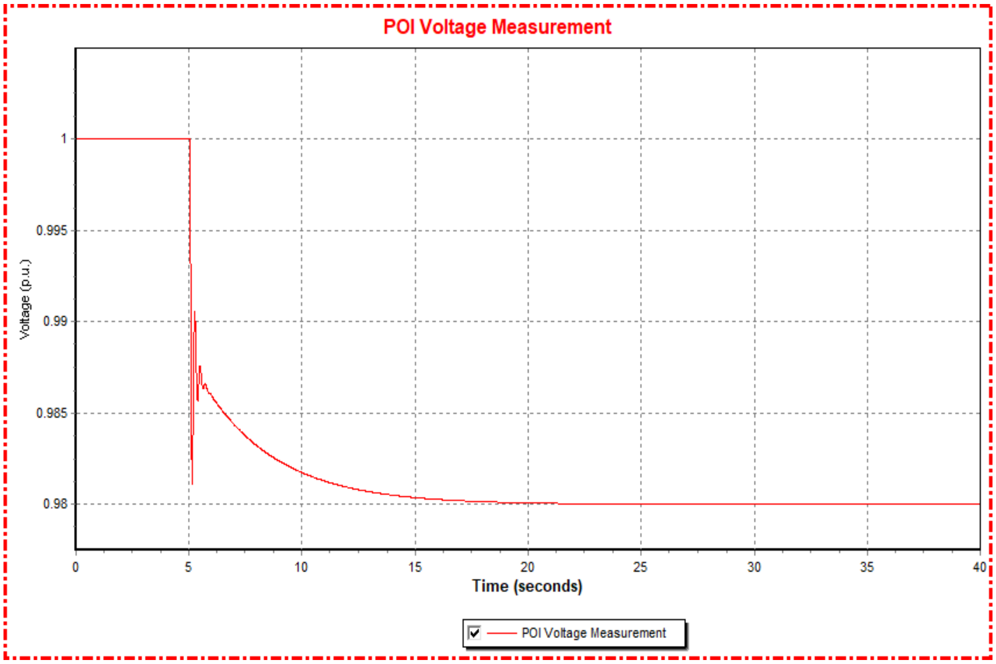

Figure 38. POI Voltage Measurement

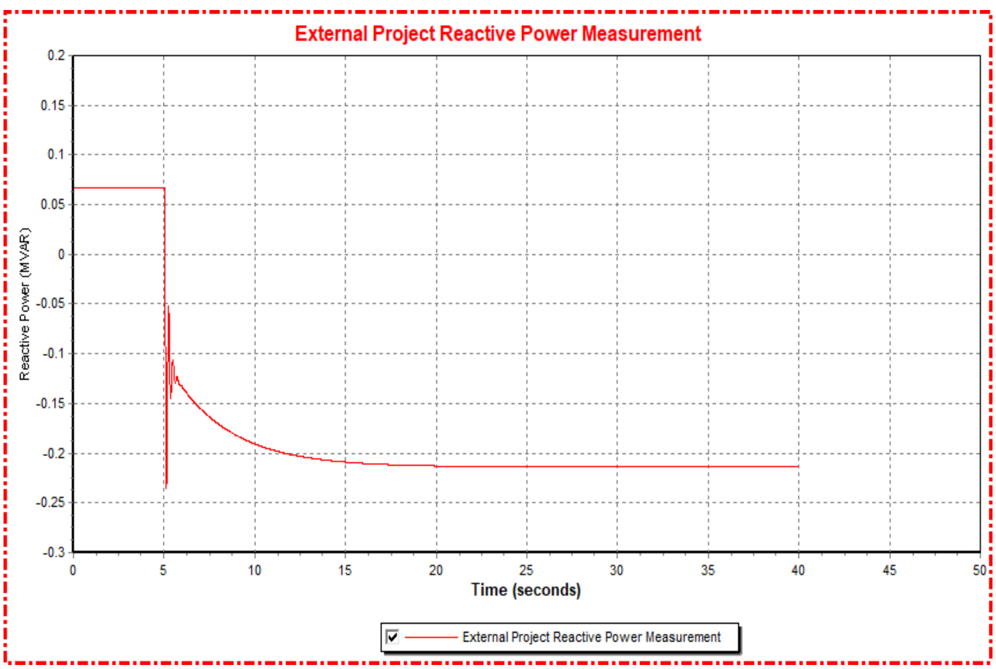

Figure 39. External Reactive Power Measurement

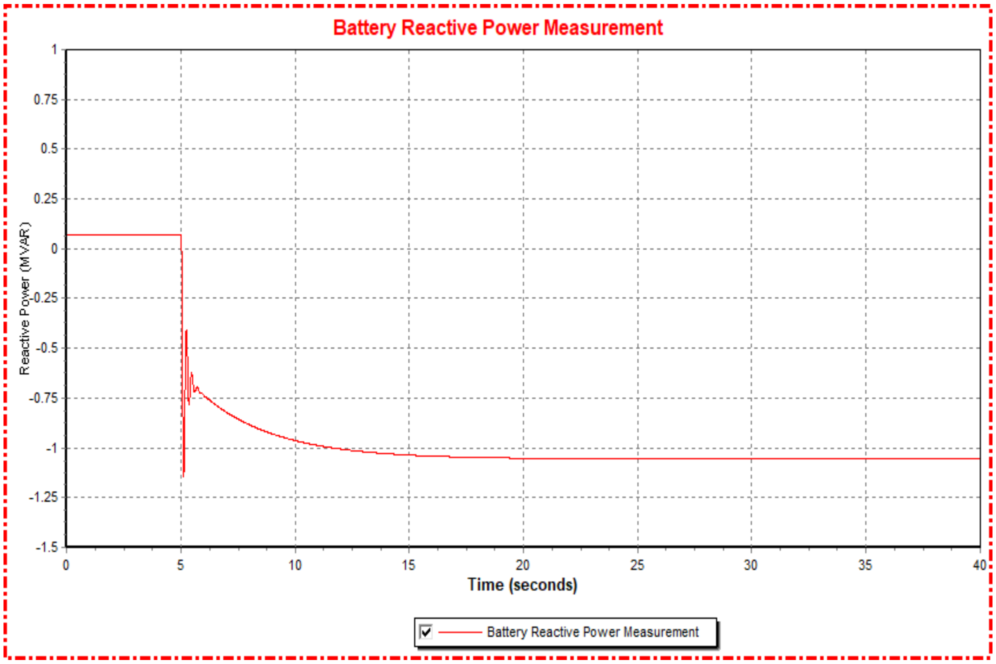

Figure 40. Battery Reactive Power Measurement

5.9 Power Firming Control

The power firming control logic is enabled by setting PRCF to 3. The user will command a remote branch, set with ICON (M) through ICON (M+2), with the active power command FRMCMD set by VAR(L+11). The Project priority flag (PRJPRIOR) will be set to 0 for battery model priority or 1 for external project priority. The prioritized project will be the first model to provide active power to maintain the commanded value at the remote branch. We assume battery priority during the test. The battery active power reference is initialized to -10 MW whereas the external project is initialized to 20 MW, thus the POI branch command is set to 10 MW. We change the remote branch command to 20 MW at 5 seconds. At 20 seconds, we command the branch to 15 MW. We command the external project to 5 MW at 30 seconds; the battery will need to respond to this change to maintain the active power at the branch. At 40 seconds we trip the battery, thus the external project will need to take over to maintain the active power at the branch. This is performed with a Power Electronics external project, with ICON (M+13) set to 1, and with an SMA external project, ICON (M+13) set to 2. Figure 41, Figure 42, and Figure 43 show the battery active power measurement, external project active power measurement, and active power branch command when controlling an external Power Electronics project. Figure 44, Figure 45, and Figure 46 show the battery active power measurement, external project active power measurement, and active power branch command when controlling an external Power SMA project.

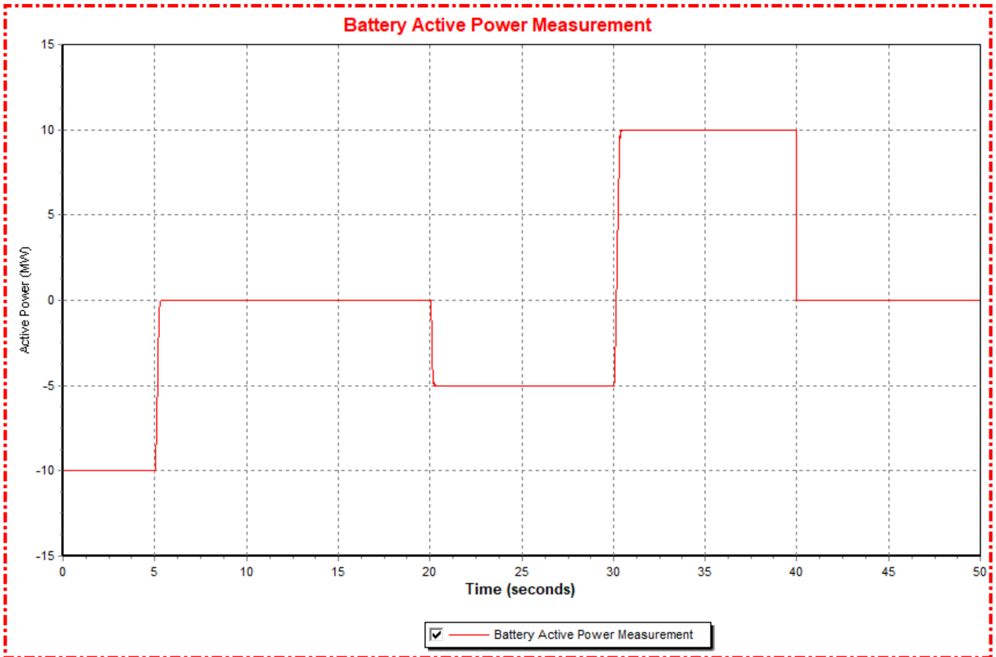

Figure 41. Battery Active Power Measurement

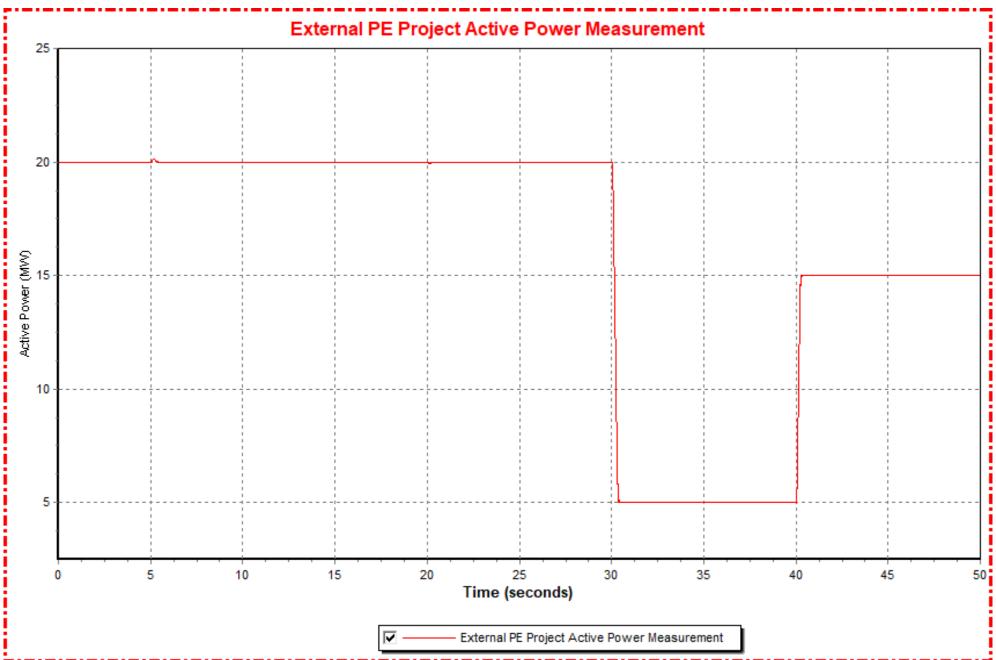

Figure 42. Power Electronics Project Active Power Measurement

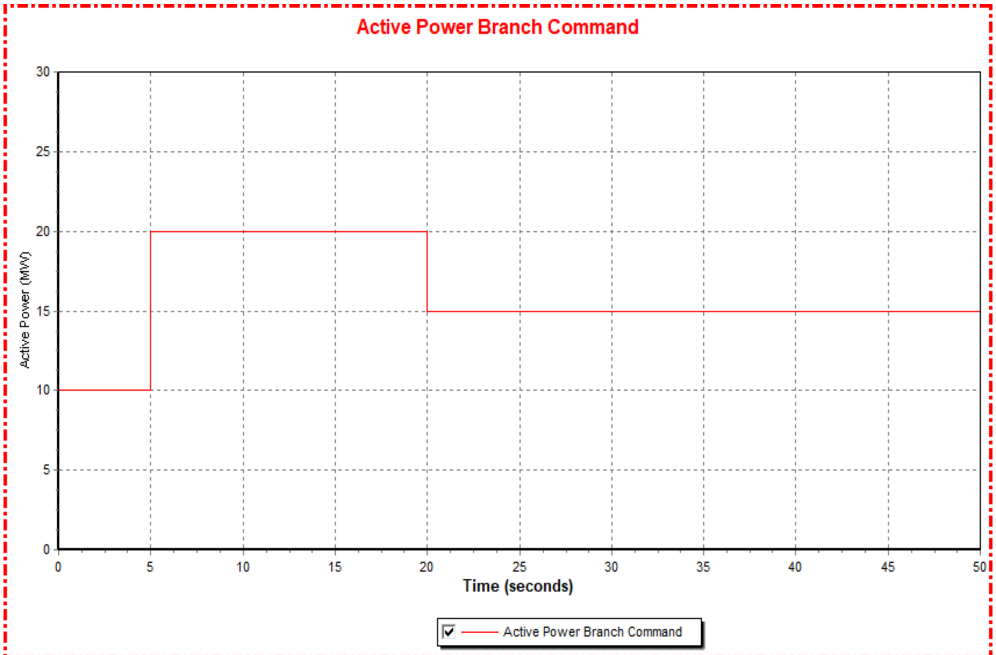

Figure 43. Active Power Branch Command

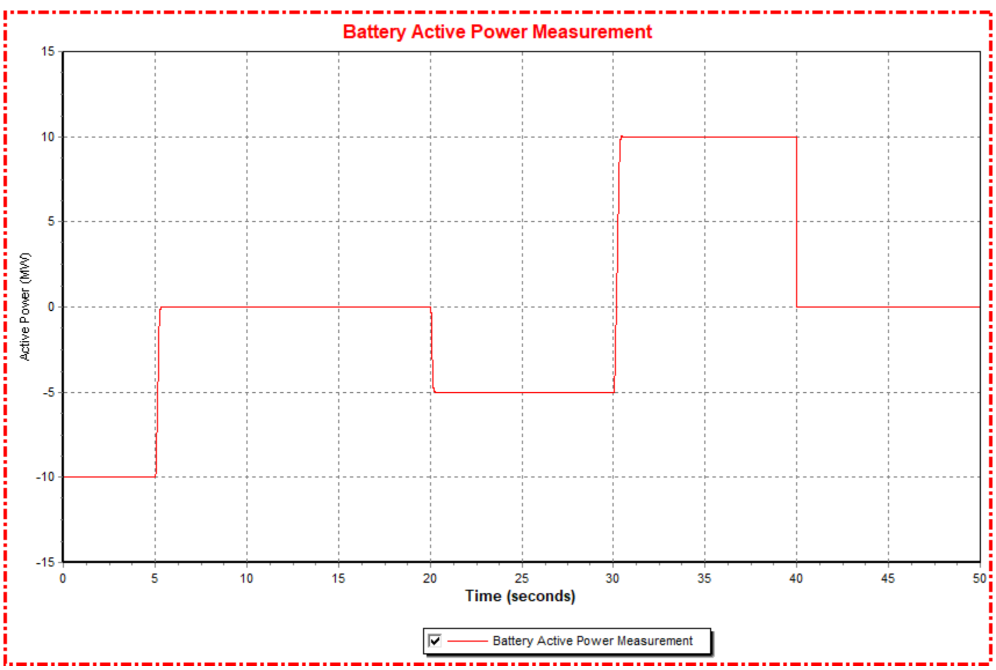

Figure 44. Battery Active Power Measurement

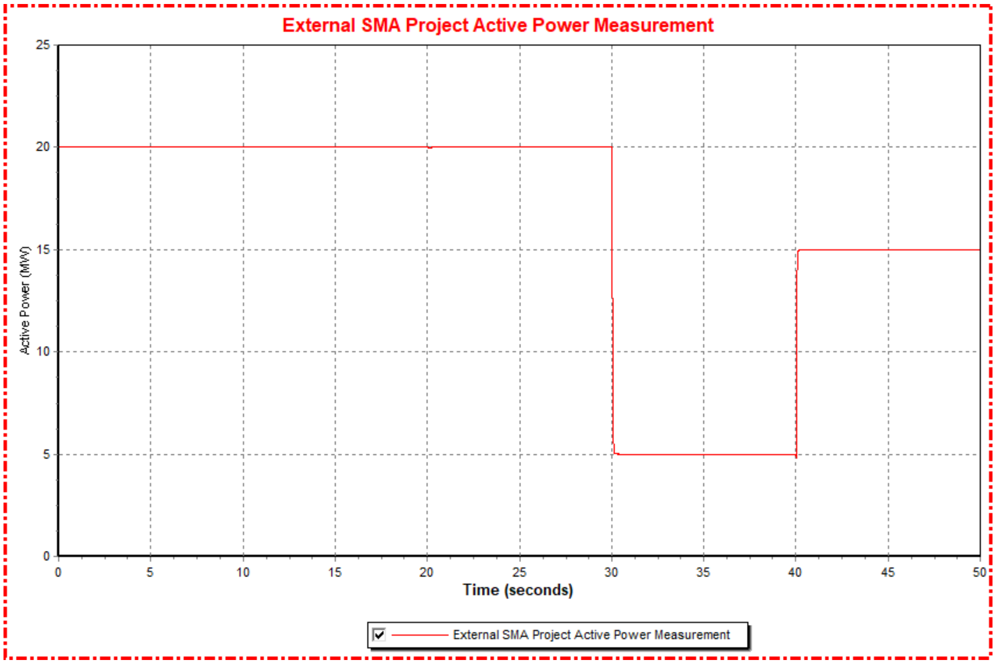

Figure 45. SMA Project Active Power Measurement

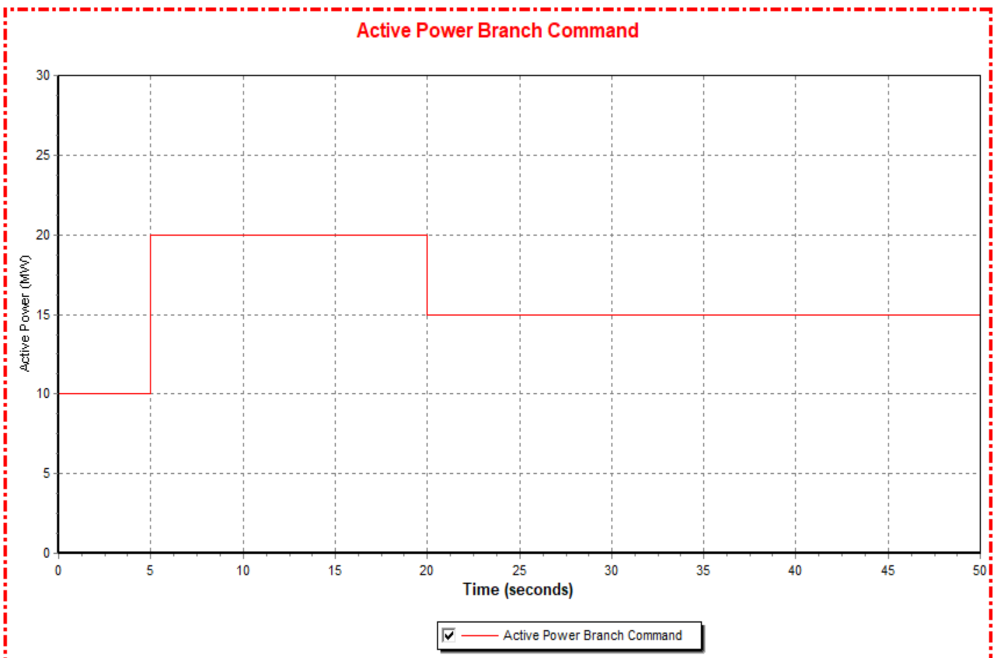

Figure 46. Active Power Branch Command

5.10 Voltage Droop Logic

The voltage droop logic is enabled by setting the VSL flag to 1 via ICON (M+7). We assume the battery provides all reactive support by setting RRL to 0. Enabling this control will add to the local/remote reactive power command based on the logic seen in Figure 5. We provide a simplistic test to demonstrate the capability by disabling all but the third under and over voltage points. We set the reactive power compensation to 5% of the Machine base at these points. This is achieved by the CON settings shown in Table 15. Voltage Droop Logic CON Parameters.

Assuming local reactive power control, voltages above 1.06 p.u. or below 0.94 p.u. should cause the BESS to absorb or provide an additional 1.75 MVAr (5% of 35 MVA via Table 12. BESS Generator Variables) respectively. The voltage measurement point may be specified through ICON (M+4). Figure 47 and Figure 48 show the BESS generator's reactive power and voltage profiles.

Table 15. Voltage Droop Logic CON Parameters

CONs	Value	Description
J+17	1.0	OVDB - Over voltage deadband for stackable voltage logic
J+18	1.05	OVV1 - Stackable voltage logic first high voltage V point
J+19	1.05	OVV2 - Stackable voltage logic second high voltage V point
J+20	1.06	OVV3 - Stackable voltage logic third high voltage V point
J+21	-0.01	OVQ1 - Stackable voltage logic first high voltage Q point
J+22	-0.02	OVQ2 - Stackable voltage logic second high voltage Q point
J+23	-0.05	OVQ3 - Stackable voltage logic third high voltage Q point
J+24	0.95	UVDB - Under voltage deadband for stackable voltage logic
J+25	0.95	UVV1 - Stackable voltage logic first low voltage V point
J+26	0.95	UVV2 - Stackable voltage logic second low voltage V point
J+27	0.94	UVV3 - Stackable voltage logic third low voltage V point
J+28	0.01	UVQ1 - Stackable voltage logic first low voltage Q point
J+29	0.02	UVQ2 - Stackable voltage logic second low voltage Q point
J+30	0.05	UVQ3 - Stackable voltage logic third low voltage Q point

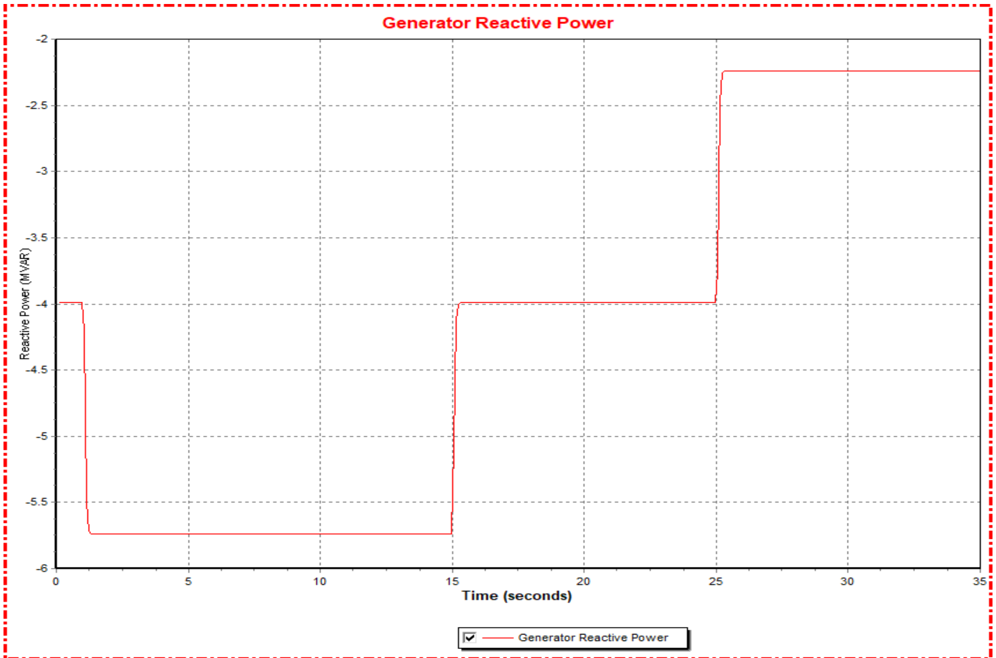

Figure 47. Generator Reactive Power

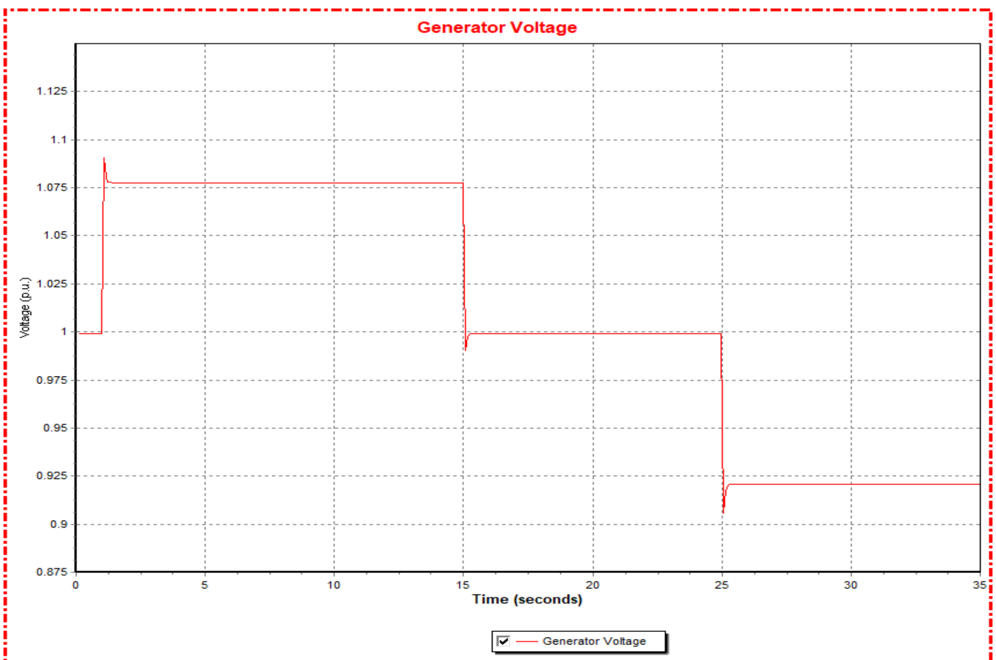

Figure 48. Generator Voltage

5.11 Frequency Droop Logic

The frequency droop logic is enabled by setting the FSL flag to 1 via ICON (M+8). Enabling this control will add to the current local/remote active power command based on the logic seen in Figure 3. Similar to the Voltage Droop Logic, we provide a simplistic test to demonstrate the capability by disabling all but the third under and over frequency points. The active power compensation is set to 5% of the Machine base at these points. This is achieved by the CON settings shown in Table 16.

Assuming local active power control, frequencies above 51.0 Hz or below 49.0 Hz should cause the BESS to absorb or provide an additional 1.75 MW (5% of 35 MVA via Table 12) respectively. The frequency measurement point may be specified by ICON (M+3). Figure 49 and Figure 50 and show the BESS generator's active power and frequency profiles.

Table 16. Frequency Droop Logic CON Parameters

CONs	Value	Description
J+31	50.5	OFDB - Over frequency deadband for stackable frequency logic
J+32	50.5	OFF1 - Stackable frequency logic first high frequency F point
J+33	50.5	OFF2 - Stackable frequency logic second high frequency F point
J+34	51.0	OFF3 - Stackable frequency logic third high frequency F point
J+35	-0.01	OFP1 - Stackable frequency logic first high frequency P point
J+36	-0.02	OFP2 - Stackable frequency logic second high frequency P point
J+37	-0.05	OFP3 - Stackable frequency logic third high frequency P point
J+38	49.5	UFDB - Under frequency deadband for stackable frequency logic
J+39	49.5	UFF1 - Stackable frequency logic first low frequency F point
J+40	49.5	UFF2 - Stackable frequency logic second low frequency F point
J+41	49.0	UFF3 - Stackable frequency logic third low frequency F point
J+42	0.01	UFP1 - Stackable frequency logic first low frequency P point
J+43	0.02	UFP2 - Stackable frequency logic second low frequency P point
J+44	0.05	UFP3 - Stackable frequency logic third low frequency P point

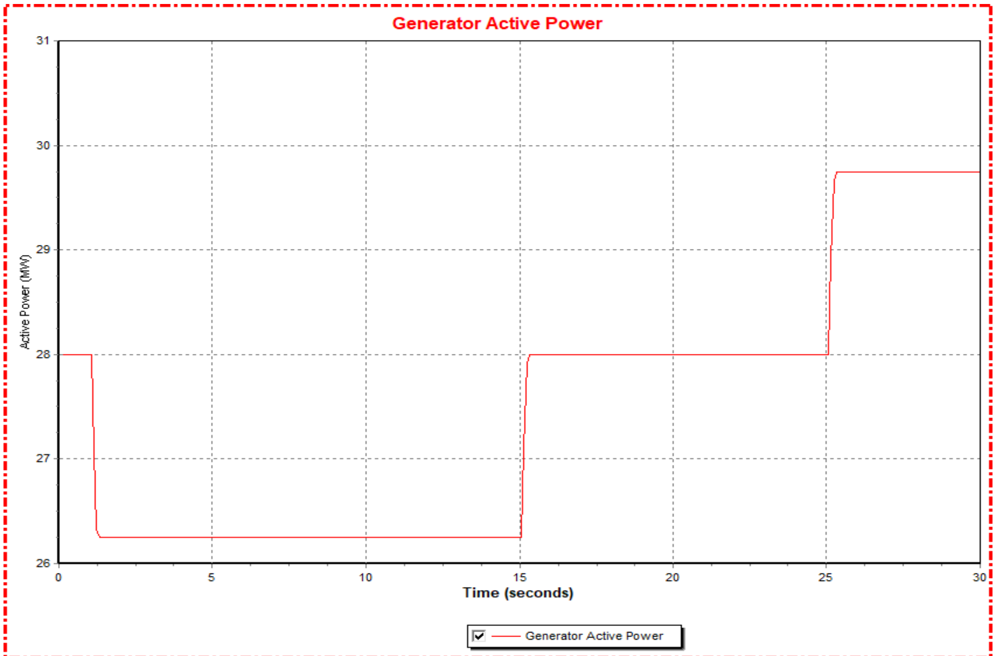

Figure 49. Generator Active Power

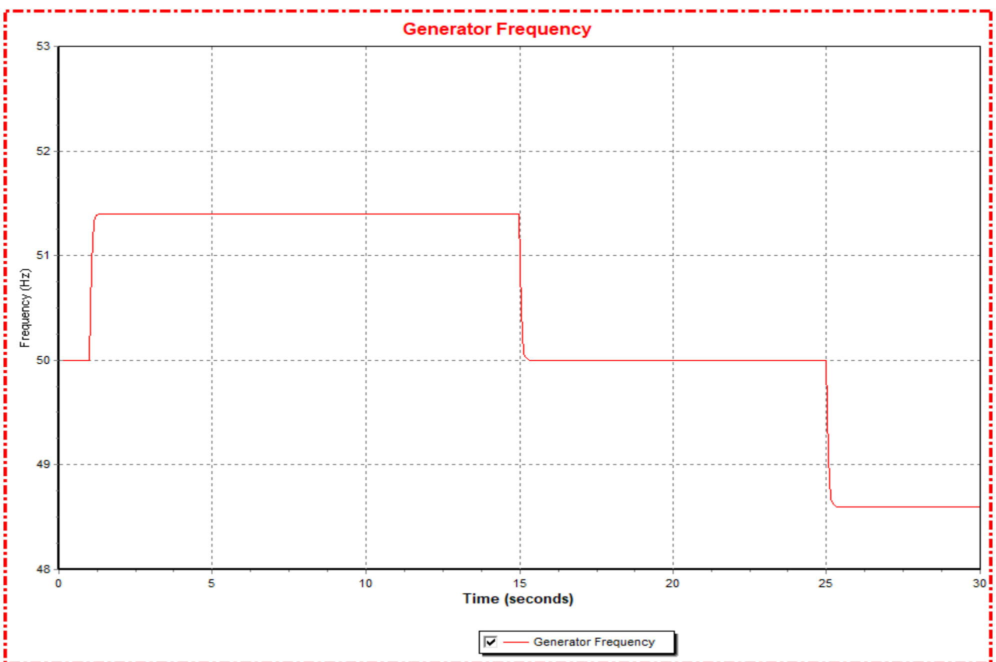

Figure 50. Generator Frequency

6. Disclaimer

This document and the developed PSS®E PPC UDM have been prepared to best represent the battery energy storage system associated with the Fluence Project. Capabilities of this model are limited to those stated in the aforementioned document. Improper use of said model or incorrect network modeling in tandem with the developed model may lead to undesired behavior. Additionally, model tuning may need to be performed in order to accurately reflect any project site conditions for each installed instance of the Fluence BESS.

7. Appendix A – PE Generator Model (PEGEN_P1000a)

Table 17. CON Definitions

CONs	Value	Description
J+0	0.8900	lv1 [p.u.]: lv1 threshold (0.00 p.u. to 1.00 p.u.)
J+1	6550.0000	t_lv1 [s]: trip time lv1 (0.0 s to 6550.0 s)
J+2	0.7000	lv2 [p.u.]: lv2 threshold (0.00 p.u. to 1.00 p.u.)
J+3	3.0000	t_lv2 [s]: trip time lv2 (0.0 s to 655.00 s)
J+4	0.6000	lv3 [p.u.]: lv3 threshold (0.00 p.u. to 1.00 p.u.)
J+5	1.0000	t_lv3 [s]: trip time lv3 (0.0 s to 655.00 s)
J+6	0.0000	lv4 [p.u.]: lv4 threshold (0.00 p.u. to 1.00 p.u.)
J+7	0.5000	t_lv4 [s]: trip time lv4 (0.0 s to 65.500 s)
J+8	0.0000	lv5 [p.u.]: lv5 threshold (0.00 p.u. to 1.00 p.u.)
J+9	0.0000	t_lv5 [s]: trip time lv5 (0.0 s to 65.500 s)
J+10	1.1100	hv1 [p.u.]: hv1 threshold (1.00 p.u. to 1.40 p.u.)
J+11	6550.0000	t_hv1 [s]: trip time hv1 (0.0 s to 6550.0 s)
J+12	1.2000	hv2 [p.u.]: hv2 threshold (1.00 p.u. to 1.40 p.u.)
J+13	0.5000	t_hv2 [s]: trip time hv2 (0.0 s to 655.00 s)
J+14	1.3000	hv3 [p.u.]: hv3 threshold (1.00 p.u. to 1.40 p.u.)
J+15	0.0100	t_hv3 [s]: trip time hv3 (0.0 s to 655.00 s)
J+16	0.0000	hv4 [p.u.]: hv4 threshold (1.00 p.u. to 1.40 p.u.)
J+17	0.0000	t_hv4 [s]: trip time hv4 (0.0 s to 65.500 s)
J+18	0.0000	hv5 [p.u.]: hv5 threshold (1.00 p.u. to 1.40 p.u.)
J+19	0.0000	t_hv5 [s]: trip time hv5 (0.0 s to 65.500 s)
J+20	59.3000	lf1 [Hz]: lf1 threshold (45.0 Hz to 60.0 Hz)
J+21	6550.0000	t_lf1 [s]: trip time lf1 (0.0 s to 6550.0 s)
J+22	58.0000	lf2 [Hz]: lf2 threshold (45.0 Hz to 60.0 Hz)
J+23	90.0000	t_lf2 [s]: trip time lf2 (0.0 s to 655.00 s)
J+24	57.0000	lf3 [Hz]: lf3 threshold (45.0 Hz to 60.0 Hz)
J+25	10.0000	t_lf3 [s]: trip time lf3 (0.0 s to 655.00 s)
J+26	55.0000	lf4 [Hz]: lf4 threshold (45.0 Hz to 60.0 Hz)

J+27	0.0100	t_lf4 [s]: trip time lf4 (0.0 s to 65.500 s)
J+28	0.0000	lf5 [Hz]: lf5 threshold (45.0 Hz to 60.0 Hz)
J+29	0.0000	t_lf5 [s]: trip time lf5 (0.0 s to 65.500 s)
J+30	60.7000	hf1 [Hz]: hf1 threshold (50.0 Hz to 65.0 Hz)
J+31	6550.0000	t_hf1 [s]: trip time hf1 (0.0 s to 6550.0 s)
J+32	62.0000	hf2 [Hz]: hf2 threshold (50.0 Hz to 65.0 Hz)
J+33	90.0000	t_hf2 [s]: trip time hf2 (0.0 s to 655.00 s)
J+34	63.0000	hf3 [Hz]: hf3 threshold (50.0 Hz to 65.0 Hz)
J+35	5.0000	t_hf3 [s]: trip time hf3 (0.0 s to 655.00 s)
J+36	64.0000	hf4 [Hz]: hf4 threshold (50.0 Hz to 65.0 Hz)
J+37	0.0100	t_hf4 [s]: trip time hf4 (0.0 s to 65.500 s)
J+38	0.0000	hf5 [Hz]: hf5 threshold (50.0 Hz to 65.0 Hz)
J+39	0.0000	t_hf5 [s]: trip time hf5 (0.0 s to 65.500 s)
J+40	60.0000	Frated [Hz]: rated frequency (50/60)
J+41	0.4000	AUX1
J+42	0.0500	AUX2
J+43	0.1000	AUX3
J+44	0.2000	AUX4
J+45	0.1000	AUX5
J+46	0.0100	AUX6
J+47	0.0000	AUX7
J+48	0.0000	AUX8
J+49	0.0000	AUX9
J+50	0.8900	lv1 [p.u.]: lv1 threshold (0.00 p.u. to 1.00 p.u.)

Table 18. ICON Definitions

ICONs	Value	Description
M	0	LV Protections: =11111 (all enabled); =00000 (all disabled)
M+1	0	HV Protections: =11111 (all enabled); =00000 (all disabled)
M+2	0	LF Protections: =11111 (all enabled); =00000 (all disabled)
M+3	0	HF Protections: =11111 (all enabled); =00000 (all disabled)

Table 19. VAR Definitions

VARs	Value	Description
L+0		Reg_hv1: Counter for hv1
L+1		Reg_hv2: Counter for hv2
L+2		Reg_hv3: Counter for hv3
L+3		Reg_hv4: Counter for hv4
L+4		Reg_hv5: Counter for hv5
L+5		Reg_lv1: Counter for lv1
L+6		Reg_lv2: Counter for lv2
L+7		Reg_lv3: Counter for lv3
L+8		Reg_lv4: Counter for lv4
L+9		Reg_lv5: Counter for lv5
L+10		Reg_hf1: Counter for hf1
L+11		Reg_hf2: Counter for hf2
L+12		Reg_hf3: Counter for hf3
L+13		Reg_hf4: Counter for hf4
L+14		Reg_hf5: Counter for hf5
L+15		Reg_lf1: Counter for lf1
L+16		Reg_lf2: Counter for lf2
L+17		Reg_lf3: Counter for lf3
L+18		Reg_lf4: Counter for lf4
L+19		Reg_lf5: Counter for lf5
L+20		Time register from previous time step
L+21		Vinv angle register
L+22		Finv register
L+23		Protection trip register
L+24 **…** **L+29**		AUX

Table 20. STATE Definitions

STATEs	Value	Description
K		Low pass filter for id command
K+1		Low pass filter for iq command
K+2		Imag (Vinv) LPF
K+3		Real (Vinv) LPF