National Grid ESO

Project Number: NG0005

Review and Analysis of Software for Dynamic Moderation and Dynamic Regulation Services

Deliverable 2a

Task 2.1: MATLAB/Simulink Model of Core FFSE Functionality

Version 1

Author:

G. M. van der Molen

Notation

1 General Notation

Acronym	*Meaning*
ABB	Asea Brown-Boveri
aBOA	Automatic (or automated) Bid Offer Acceptance
ACE	Area Control Error
aFRR	Automatic Frequency Restoration Reserves
AGC	Automatic Generation Control
ANBE	Assistant National Balancing Engineer (formerly: ZBE)
API	Application Programming Interface
ARIMA	Auto-Regressive Integrated Moving-Average
ASB	Ancillary Services Business
AZ	Atomic Zone
BALIT	Balancing Inter TSO (Transmission System Operator(s))
BC	Boundary Constraint
BE	Balancing Engineer
BEIS	Department for Business, Energy & Industrial Strategy
BM	Balancing Mechanism
BMRS	Balancing Mechanism Reporting Service
BMU	Balancing Mechanism Unit
BOA	Bid Offer Acceptance
CCGT	Combined Cycle Gas Turbine
CCL	Capped Committed Level
CGO	Combined Generation Output
CLOGS	Contingency LOGging System
CMN	Capacity Market Notice
CMW	Capacity Market Warning
CPLEX	Mixed integer linear program optimiser
CZ	Constraint Zone
DAS	Day-Ahead Schedule(r)
DC	1. Dynamic Containment (in this report, unless specified otherwise) 2. Dispatch Control
DECC	Department of Energy & Climate Change (since July 2016 part of BEIS)
DM	Dynamic Modulation
DR	1. Dynamic Regulation (in this report, unless specified otherwise) 2. Dynamic (Frequency) Response
DSO	Distribution System Operator

DTS	Dispatch(er) Training Simulator
DTSE	Dispatch(er) Training Simulator Emulator (in MATLAB/Simulink)
EBS	Electricity Balancing System
ED	Economic Dispatch
EDL	Electronic Data Logging
EFR	Enhanced Frequency Response
EFS	Energy Forecasting System
EMN	Electricity Margin Notice (before 30/9/2016: NISM)
EMS	Energy Management System
ENCC	Electricity National Control Centre
EU	European Union
F/C	Forecast
FCDM	Frequency Control by Demand Management
FCI	Frequency Control Instruction
FCR	Frequency Containment Reserve
FC2020	Frequency Control in 2020
FFR	Firm Frequency Response (Fast Frequency Response in some countries)
FFSE	Fast Frequency Simulation Engine
FM	Frequency Management
FPN	Final Physical Notification
FRR	Frequency Restoration Reserve
FSE	Frequency Simulation Engine
FSL	Frequency Sensitivity of Load
GB	Great Britain
H	High-frequency response
HF	High Frequency
HVDC	High-Voltage Direct Current
IA	Independent Action
ICCP	Inter-Control Centre Communication Protocol
I-Conn	Interconnector
IDS	In-Day (or Intraday) Schedule(r)
IEMS	Integrated Energy Management System
IS	Information Systems (NG's IT department)
ISO	Independent System Operator
IT	Information Technology
KPI	Key Performance Indicator
LDP	Load Demand Predictor
LF	Low Frequency
LFC	Load Frequency Control

LMP	Locational Marginal Price/pricing
LUT	LookUp Table
MBM	Manual/Balancing Mechanism
mBOA	Manual Bid Offer Acceptance
MEL	Maximum Export Limit
MELNGC	Indicated Constraint Boundary Margin; The Import and Export constraint limits for a BMRS Zone. The Import constraint limit being calculated as the boundary transfer limit minus the Demand Forecast plus the sum of Maximum Export Limits for exporting BM Units and the export constraint limit being calculated as the boundary transfer limit plus the Demand Forecast minus the sum of Maximum Export Limits for exporting BM Units. Data supplied by the System Operator for the day ahead and current day (a number of times each day) for publication on the BMRS, comprising the Indicated Constraint Boundary Margin for each System Zone and the national value for each Settlement Period.
mFRR	Manual Frequency Restoration Reserves (mFRR)
MIL	Maximum Import Limit
MNZT	Minimum Non-Zero Time
MPC	Model (-based) Predictive Control
MS	Microsoft
MW	MegaWatt (power level)
MZT	Minimum Zero Time
NBE	National Balancing Engineer
ND	Nominal Demand at 50 Hz
NDZ	Notice to Deviate from Zero
NISM	Notification of Inadequate System Margin (since 30/9/2016: EMN)
NPP	Nuclear Power Plant
NSM	Network Security Manager for EBS
NTB	Notice To Bid
NTE	Near-Term Event
NTO	Notice To Offer
OEM	Operational Energy Manager
OEM Program	The program of MW values for the seven zones issued by the OEM to the NBE at around two hours ahead of real time.
OSA	Online Stability Analysis
P	1. Primary (low-frequency response) (= PRY) 2. Proportional
PBS	Power Balancing System
PCS	(BOA) Power Control Signal; The modelled power signal to represent the power demand for the relevant Super-BMU.
PH	Primary and High frequency response
PID	Proportional-Integral-Derivative (control)
PJM	Pennsylvania New Jersey Maryland Interconnection LLC (Mid-Atlantic region power pool)

PM	Program Management
PN	Physical Notification
pph	Power per hz
PRY	Primary (low-frequency) response
PS	Pumped Storage
PSH	Primary, Secondary and High frequency response
PSM	Power System Manager
PU	Per Unit
PV	Photo-Voltaic (power generation)
rBOA	Rapid Bid Offer Acceptance
RD	Resource Dispatch
RDR	Run Down Rate or Ramp-Down Rate
Red Box	An analysis point inserted by a control engineer (the NBE, for times close to real time) into a zonal program to force the DISPATCH optimiser to create a solution for that point in time. Red Boxes are typically placed five minutes before and after the half hour. The zonal programs are linearly interpolated between the Red Box points.
rFR	Rapid Frequency Response
ROCOF/RoCoF	Rate Of Change Of Frequency
RR	Replacement Reserves
RTC	Real-Time Commitment (15 min periodicity in current EBS design; summer 2017)
RTD	Real-Time Dispatch (5 min periodicity in current EBS design; summer 2017)
RUR	Run Up Rate or Ramp-Up Rate
R&D	Research and Development
S	Secondary (low-frequency) response (= SEC)
SBMU	Super-BMU or Super-Balancing Mechanism Unit
SCADA	Supervisory Control And Data Acquisition
SCUC	Security Constrained Unit Commitment
SEC	Secondary (low-frequency) response
SEL	Stable Export Limit
SIL	Stable Import Limit
SL	Simulink
SOP	System Operating Plan
SORT	System Operation Real Time (database and displays)
SO-SO	System-Operator-to-System-Operator
SP	Set Point
SQSS	Security and Quality of Supply Standard
SRD	Standing Reserve Dispatch (used to instruct non-BM STOR providers)
STOR	Short-Term Operating Reserve
STWF	Short-Term Wind Forecasting

TERRE/Terre	Trans-European Replacement Reserves Exchange
TR	Triggered (or Tripped) Response (or Static Frequency Response)
TSO	Transmission System Operator
Tx	Transmitter/Transmission/Interconnector
VPC	Valve Positioning Control
ZBE	Zonal Balancing Engineer (2 of, North and South, under normal operating conditions; a third ZBE is used to manage the North and South wind zones at times of high wind volatility). Now referred to as ANBE.

Time-dependencies: In the main text and in equations, explicit time dependencies of variables, e.g. x, are indicated through the time variable t in brackets, e.g. as $x(t)$. However, where time dependencies apply to vectors with (obviously) the same time points or are otherwise trivial, e.g. as in $y(t) = 2x(t) - 1$, the time variable t is usually omitted, e.g. as in $y = 2x - 1$.

2 Subscript Letter (Combinations) Notation

Letters/numbers	**Meaning**
0	The current 'time now'
1, 2	Elements of a (to be) combined signal/variable
11	Start of first ramp of (ramp--constant—ramp-back) BOA
12	End of first ramp of (ramp--constant—ramp-back) BOA
21	Start of second ramp of (ramp--constant—ramp-back) BOA
22	End of second ramp of (ramp--constant—ramp-back) BOA
BC	Boundary Constraint
BMU	Balancing Mechanism Unit
BOA	Bid Offer Acceptance
Bound	Boundary
cBOA	Cumulative BOA (Bid Offer Acceptance)
CCL	Capped Committed Level
CZ	Constraint Zone
Dem	Demand
e	Error
Fil	Filtered or smoothed
Fun	Funnel
i (1)	Index, i.e. one particular instance of a set or vector
i (2)	Interpolated to or sampled at a constant sample time
IF	Imbalance Funnel
ll	Lower limit
neg	Negative

p	Profile, i.e. vector combined with corresponding time vector
PN	Physical Notification
pos	Positive
Pred	Prediction
PS	Pumped Storage
RDR	Ramp Down Rate
RUR	Ramp Up Rate
skip	Relating to time/period from the current 'decision-making' time over which any BOAs issued cannot affect BMU power; comprised of 'BOA calculation' time and NTO/B time
SZ	SORT Zone
Th	Thermal
TI	Thermal Imbalance
tol	Tolerance
ul	Upper limit
Unc	Unconstrained
Unf	Unfiltered
v	Vector, as opposed to scalar
x	Amplitude (signed, i.e. positive or negative)
Z	(SORT) Zone

3 Figure and Scope Colour Notation

Table 1: General colour codes/abbreviations

Letter	Colour
B	Blue
Br	Brown
C	Cyan
G	Green
Gy	Grey
K	Black
L	Lilac
M	Magenta
O	Orange
P	Purple
Pi	Pink (paler than magenta)
R	Red
W	White
Y	Yellow

Preceding letters (lower case):

d = dark

l = light

m = mid/medium

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Version History

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1	30/6/2021	GMM	PM	ACC

Changes from the Previous Authorized Version

Section(s)	Description of Change(s)
-	None – Original version.

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1 Introduction

1.1 Background

National Grid Electricity System Operator (NGESO) has designed a suite of new frequency response products, including Dynamic Containment (DC), Dynamic Moderation (DM) and Dynamic Regulation (DR), in response to the changing requirements. Internal effort has been invested in developing a support software tool called Fast Frequency Simulation Engine (FFSE) with modelling/simulation and optimisation functions. The FFSE can be used to analyse the capability of these new frequency service products. It also generates information for control room use.

NGESO engaged ISC to assess the capability of the new DM and DR services to meet the design requirements using the FFSE tool. In an earlier Phase 1 of the project 'DM/DR Evaluation and Development', the existing FFSE capabilities were enhanced by a Simulink model of the basic grid system with the DM and DR services. The Simulink model allowed for the linear analysis of the system, which in turn provided an explanation for (some of) the potential oscillations and instabilities that had been observed in the FFSE tools, when using high DM and DR gains. This feature of Simulink and its general user-friendliness and accessibility for non-expert (in R and C++) users was found useful enough to extend the Simulink model to include all FRS services of the FFSE (ShinyAppLegacy) as Task 2.1 of the current Phase 2 project (ISC [3]).

This report describes the development and validation of the Simulink model enhanced with the additional FRS services.

1.2 Main Sections of Report

The main body of the report is structured as follows:

- Section 1 Introduction (this section)
- Section 2 Frequency Response Services
- Section 3 Grid and FRS Model Descriptions
- Section 4 Simulink Simulation Test Results
- Section 5 Potential Model Improvements
- Section 6 Conclusions

1.3 Acknowledgements

This report was written with the significant assistance of Navid Eila, William Dale, Joe Alan Roman Flores and Neil Morgans of National Grid ESO, in providing information about the operation of the FFSE tool, data and feedback.

2 Frequency Response Services Overview

The following table of the Frequency Response Services (FRSs) that are represented in the FFSE ShinyAppLegacy tool was copied from Phase 1 Deliverable 1e "Task 1.3 Required DM/DR Services & Test Scenarios" (van der Molen [1]), with the exception of FFR Ref. The table gives an overview of the main timescales and frequency intervals over which NG ESO's various existing and 'new' dynamic (DR/DM/DC) frequency response services are active.

NG frequency limits:

- Operational range: 50 Hz ±0.2 Hz
- Statutory (pre-fault) range: 50 Hz ±0.5 Hz

Table 2: Frequency Response Service Timescales

Service	Procurement timescale	Active Frequency range 0-100% [Hz] (deviation from 50 Hz)	Delay/ Lag [s]	Ramp Time [s]	Duration
MFR Primary Response	< 1 Day (FFR: 1-30 months)	0.015-0.2	1.5	10	30 s
MFR Secondary Response	< 1 Day (FFR: 1-30 months)	0.015-0.2	10	30	30 min
MFR High Response	< 1 Day (FFR: 1-30 months)	0.015-0.2	1.5	10	> 30 min
Static 1/2/3	Day-ahead (FFR: 1-30 months)	Various	1	N/A	30 min
EFR	Procured in 2018	Service 1: 0.05-0.5 Service 2: 0.015-0.5	0.5	1	20 min
FFR Ref					
BritNED	> 1 Day	Unknown	1.5	Unknown	Inf
Dynamic Regulation	Day ahead	0.015-0.1 (or 0.2)	2	8	Inf
Dynamic Moderation	Day ahead	0.1-0.2	0.5	0.5	20 min
Dynamic Containment	Day ahead	0.015-0.2-0.5 (w 5% knee)	0.25-0.5	0.25-0.5	20 min

3 Grid and FRS Model Descriptions

Note about time dependencies: The Simulink model consists of a combination of continuous-time and discrete-time components. The model components that relate to the transitions between continuous time and discrete time are not listed specifically in the model descriptions. The time dependencies of model variables have been indexed by 't' for continuous-time variables and 'k' for discrete-time variables (adjustable sample times with default 0.01 s). In the case of some purely algebraic equations, i.e. no time dependencies in the equations themselves, the time indices have been omitted.

3.1 Grid Model

3.1.1 Swing Equation

The fundamental calculation of the grid Frequency 'w' as a function of other factors is the Swing Equation (Wikipedia [5]), which basically says that the rate or change of Frequency is proportional with the net (imbalance) power supplied to the grid. The proportionality constant is determined by the grid inertia constant 'J_{grid}'.

$$J_{grid}\frac{dw}{dt} = \frac{w_n}{2}P_{net}$$

$$P_{net} = P_{Loss} + P_{FSL} + P_{RoCoF} + P_{FRS}$$

where

w = Grid Frequency [Hz]

w_n = Nominal grid Frequency [Hz]

J_{grid} = Grid inertia constant [MVAs]

P_{net} = Net grid power or imbalance [MW]

P_{Loss} = Power loss or imbalance due to external causes [MW]

P_{FSL} = Frequency Sensitivity of Load power [MW]

P_{RoCoF} = Power change/loss due to Rate of Change of Frequency event [MW]

P_{FRS} = Total Frequency Response Service (FRS) power [MW]

3.1.2 Frequency Sensitivity of Load

The Frequency Sensitivity of Load (FSL) describes how the total load (power) on the grid depends on (i.e. is affected by) the grid Frequency. Generally, the (negative) load power increases with increasing Frequency and vice versa. While the exact relationship is unknown (and varies with time, the mix of demand and generation units, etc.), the load power can be approximately modelled as proportional with Frequency deviation from the nominal Frequency. The proportionality constant is the product of demand power 'P_{Dem}' and an estimated, constant factor 'pph' of per-unit load against Frequency deviation.

$$P_{FSL} = -P_{Dem} * pph * (w - w_n)$$

where

P_{Dem} = Nominal power demand on grid [MW]

pph = Gain of relative (per unit) load power change as function of Frequency change [1/Hz]

3.1.3 Rate of Change of Frequency

If the amplitude of the Rate of Change of Frequency (RoCoF) exceeds a certain value, some generation and demand units trip/disconnect automatically from the grid. In principle, different units could disconnect at different rates (easily implementable in Simulink). However, in the current models, both ShinyAppLegacy and Simulink, only a single RoCoF value and corresponding trip volume are modelled. Since overall there is more generation than demand volume that tends to trip, the trip volume is negative.

The detection of a RoCoF trip event may be based on the RoCoF trip value being exceeded over a window of time rather than a single instant. In the models, this is represented on a test at the start and end times of the window rather than the full duration.

$$f_{RoCoF1,k} = \left(\left| \frac{dw}{dt}_{k-k_{del}} \right| \geq RoCoF_{\lim} \quad \& \quad \left| \frac{dw}{dt}_{k-k_{del}-k_{window}} \right| \geq RoCoF_{\lim} \right)$$

$$f_{RoCoF2,0} = false$$

$$f_{RoCoF2,k(>0)} = \begin{cases} true & if \quad f_{RoCoF1,k} \ or \ f_{RoCoF2,k-1} \\ false & else \end{cases}$$

$$P_{RoCoF,k} = \begin{cases} P_{RoCoFvol} & if \quad f_{RoCoF2,k} \\ 0 & else \end{cases}$$

where

$RoCoF_{lim}$ = RoCoF limit above which a RoCoF event is triggered [Hz/s]

f_{RoCoF1} = Flag to indicate whether RoCoF is exceeding its trigger limit [-]

f_{RoCoF2} = Flag to indicate whether a RoCoF event has been triggered [-]

$P_{RoCoFvol}$ = RoCoF power volume when triggered [MW]

P_{RoCoF} = RoCoF power [MW]

3.2 FRS Models

The total Frequency Response Services (FRS) power contribution consists of the sum of its individual components:

$$P_{FRS} = P_{PSH} + P_{TR} + P_{EFR} + P_{FFR} + P_{IC} + P_{DC} + P_{DM} + P_{DR}$$

where

P_{PSH} = PSH Dynamic Response [MW]

P_{TR} = Triggered or Static Response [MW]

P_{EFR} = Enhanced Frequency Response [MW]

P_{FFR} = Firm Frequency Response [MW]

P_{IC} = Interconnector Response [MW]

P_{DC} = Dynamic Containment Response [MW]

P_{DM} = Dynamic Modulation Response [MW]

P_{DR} = Dynamic Regulation Response [MW]

3.2.1 PSH Response

The Primary/Secondary/High (PSH) Dynamic Response services provide a power that is in principle proportional with the Frequency deviation from its nominal value, although the gain varies with the magnitude of the deviation. Primary Response is designed to act fast during the first 30 seconds of a (large) low Frequency deviation, with Secondary Response then taking over. High (Frequency deviation) Response is to last for the full required duration.

$$w_{PH,k} = w_n - w_{k-k_{delPH}}$$

$$w_{S,k} = w_n - w_{k-k_{delS}}$$

$$P_{Pdash} = \frac{1}{1-a}\begin{bmatrix} frac_{P8}P_{Pvol} - aP_{Svol} \\ P_{Pvol} - aP_{Svol} \\ frac_{P2}P_{Pvol} - frac_{S2}aP_{Svol} \end{bmatrix}$$

$$P_{Sdash} = \begin{bmatrix} P_{Svol} \\ P_{Svol} \\ frac_{S2}P_{Svol} \end{bmatrix}$$

$$P_{Hdash} = \begin{bmatrix} frac_{H2}P_{Hvol} \\ P_{Hvol} \end{bmatrix}$$

$$P_{targetP,k} = \min\left(\max\left(hd_{L8} - hd_{fade}w_{PH,k}, 0\right), 1\right) * P_{Pdash}(1)$$
$$+\left(\min\left(\max\left(hd_{L5} - hd_{fade}w_{PH,k}, 0\right), 1\right) - \min\left(\max\left(hd_{L8} - hd_{fade}w_{PH,k}, 0\right), 1\right)\right) * P_{Pdash}(2)$$
$$+\left(\min\left(\max\left(hd_{L2} - hd_{fade2}w_{PH,k}, 0\right), 1\right) - \min\left(\max\left(hd_{L5} - hd_{fade}w_{PH,k}, 0\right), 1\right)\right) * P_{Pdash}(3)$$

$$P_{targetH,k} = \left(\min\left(\max\left(hd_{fade}w_{PH,k} - hd_{H2}, 0\right), 1\right) - \min\left(\max\left(hd_{fade}w_{PH,k} - hd_{H5}, 0\right), 1\right)\right) * P_{Hdash}(1)$$
$$+\min\left(\max\left(hd_{fade}w_{PH,k} - hd_{H5}, 0\right), 1\right) * P_{Hdash}(2)$$

$$P_{targetPH,k} = P_{targetP,k} + P_{targetH,k}$$

$$P_{PH,k} = \min\left(\max\left(P_{targetPH,k}, P_{PH,k-1} - dP_{PH}t_{sR}\right), P_{PH,k-1} + dP_{PH}t_{sR}\right)$$

$$P_{targetS,k} = \min\left(\max\left(hd_{L8} - hd_{fade}w_{PH,k}, 0\right), 1\right) * P_{Pdash}(1)$$
$$+\left(\min\left(\max\left(hd_{L5} - hd_{fade}w_{S,k}, 0\right), 1\right) - \min\left(\max\left(hd_{L8} - hd_{fade}w_{S,k}, 0\right), 1\right)\right) * P_{Pdash}(2)$$
$$+\left(\min\left(\max\left(hd_{L2} - hd_{fade2}w_{S,k}, 0\right), 1\right) - \min\left(\max\left(hd_{L5} - hd_{fade}w_{S,k}, 0\right), 1\right)\right) * P_{Pdash}(3)$$

$$P_{S,k} = \min\left(\max\left(P_{targetS,k}, P_{S,k-1} - dP_{S}t_{sR}\right), P_{S,k-1} + dP_{S}t_{sR}\right)$$

$$P_{PSH,k} = P_{PH,k} + P_{S,k}$$

where

w_{PH} = Frequency error delayed by PH delay [Hz]

w_S = Frequency error delayed by S delay [Hz]

$k_{delPH,S}$ = Frequency delay/lag for PH respectively S response, in discrete time steps [s]

$P_{Pvol,Svol,Hvol}$ = P, S & H volumes [MW]

$frac_{P8,P2,S2,H2}$ = Fractions of P, S & H volumes at 0.8 (P8) and 0.2 Hz Frequency deviations, relative to 0.5 Hz deviation [-]

a = Help parameter [-]

P_{Pdash}, P_{Sdash}, P_{Hdash} = Help parameters [MW]

$P_{targetP}$, $P_{targetS}$, $P_{targetH}$, $P_{targetPH}$ = Target power levels of corresponding PSH components before application of rate limits [MW]

hd_{fade}, hd_{fade2} = Help parameters [Hz]

hd_{L8}, hd_{L5}, hd_{L2}, hd_{H2}, hd_{H5} = Help parameters [-]

dP_{PH} = PH ramp rate limit [MW/s]

dP_S = S ramp rate limit [MW/s]

t_{sR} = Discrete time step of PSH calculations [s]

P_{PH} = PSH component due to PH [MW]

P_S = PSH component due to S [MW]

3.2.2 Static Response

The principle of the Static or Triggered Response (TR) is that it acts very fast once certain trigger Frequencies are exceeded. In the ShinyAppLegacy each such Frequency is modelled as a separate unit; in Simulink all 'Primary' or low-Frequency 'units' are combined into a single lookup table. Similarly, in Simulink all 'High' (-Frequency) units are also combined in a single (separate) lookup table.

$$w_{e,k} = w_n - w_{k-k_{delTR}}$$

$$P_{P1,k} = \begin{cases} 0 & if \quad w_{e,k} < w_{PLUT1} \\ P_{PLUT1} & if \quad w_{PLUT1} \le w_{e,k} < w_{PLUT2} \\ P_{PLUT2} & if \quad w_{PLUT2} \le w_{e,k} \end{cases}$$

$$P_{P2,k} = \max(P_{P1,k}, P_{P2,k-1})$$

$$P_{H1,k} = \begin{cases} 0 & if \quad w_{e,k} > w_{HLUT1} \\ P_{HLUT1} & if \quad w_{HLUT1} \ge w_{e,k} > w_{HLUT2} \\ P_{HLUT2} & if \quad w_{HLUT2} \ge w_{e,k} \end{cases}$$

$$P_{H2,k} = \min(P_{H1,k}, P_{H2,k-1})$$

$$P_{TR,k} = P_{P2,k} + P_{H2,k}$$

where

w_e = Frequency error or deviation from nominal value, delayed by TR delay [Hz]

$w_{PLUT1,2,HLUT1,2}$ = Coordinates of TR P & H lookup table Frequency values that trigger TR [Hz]

$P_{PLUT1,2,HLUT1,2}$ = Corresponding TR P & H response values [MW] [Hz]

$P_{P1,H1}$ = TR P & H responses resulting from immediate Frequency [MW]

$P_{P2,H2}$ = Final P & H responses maintaining the max value [MW]

Note 1: In the current model, Primary and High Triggered Response can only increase in magnitude; there is no reduction or reset to zero. However, Primary and High Triggered Response can operate simultaneously.

Note 2: Static Response in the ShinyAppLegacy has options of a ramp time (instead of a step) and a trig window (equivalent to the RoCoF trig window, but here acting on Frequency itself rather than its rate of change) as well. These features have not been included in the current Simulink model but could be added easily if required.

3.2.3 Enhanced Frequency Response

Enhanced Frequency Response (EFR) is based on the same principles as the 'New Dynamics' DC, DM and DR in Sections 3.2.6-3.2.8. However, EFR has an additional complexity in that EFR units are allowed to 'drift' or take any response position within an envelope around the central response curve:

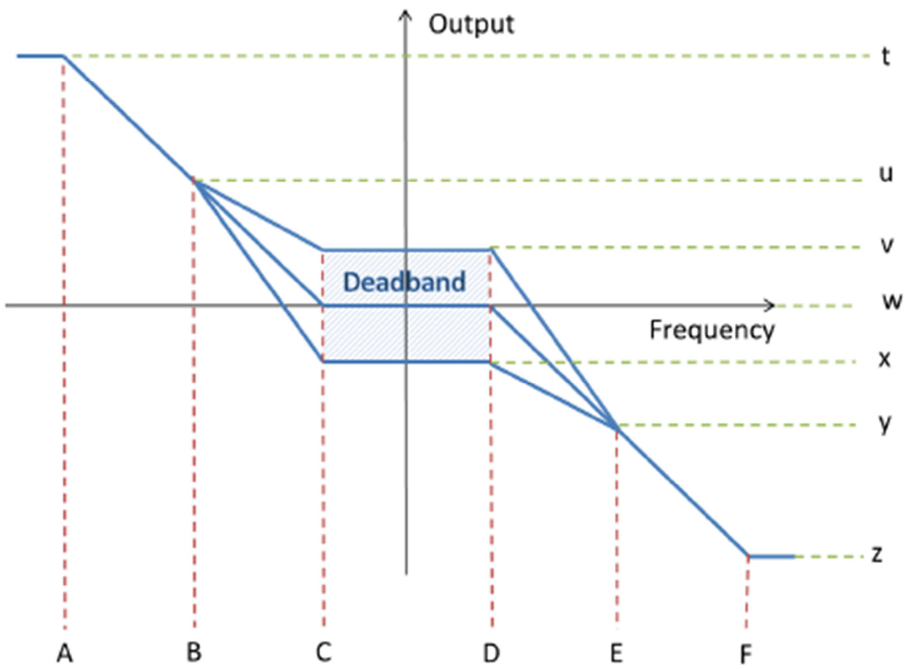

Figure 1: EFR Envelope (National Grid [4])

See e.g. National Grid [4] for details.

$$w_{e,k} = w_n - w_{k-k_{delEFR}}$$

$$P_{eqv\_curve,k} = LUT_{eqv\_curve}(w_{e,k})$$
$$P_{upperEnv,k} = LUT_{upperEnv}(w_{e,k})$$
$$P_{lowerEnv,k} = LUT_{lowerEnv}(w_{e,k})$$

$$f_{helping,k} = \begin{cases} 0 & if \quad \left|w_{e,k}\right| > 0.1 \\ f_{helping,k-1} & else \end{cases}$$

$$P_{target\_resp1,k} = \begin{cases} P_{upperEnv,k} & if \quad \left(w_{k-k_{delEFR}} \le w_n \ \&\ f_{helping,k} = 1\right) \ or \ \left(w_{k-k_{delEFR}} > w_n \ \&\ f_{helping,k} = 0\right) \\ P_{lowerEnv,k} & else \end{cases}$$

$$P_{target\_resp,k} = \begin{cases} P_{target\_resp1,k} & if \quad f_{helping,k} = 1 \\ P_{EFR0} & else \end{cases}$$

$$P_{temp2,k} = P_{resp,k-1} + P_{eqv\_curve,k} - P_{eqv\_curve,k-1}$$

$$P_{temp1,k} = \max\left(\begin{matrix} \min\left(\max\left(\min\left(P_{target\_resp,k}, P_{temp2,k} + P_{env\_ramp\_rate}\right), P_{temp2,k} - P_{env\_ramp\_rate}\right), P_{upperEnv,k}\right), \\ P_{lowerEnv,k} \end{matrix}\right)$$

$$f_{overdeliv,k} = \left(w_{k-k_{delEFR}} < w_n \ \&\ P_{resp,k-1} > P_{upperEnv,k}\right) \ or \ \left(w_{k-k_{delEFR}} > w_n \ \&\ P_{resp,k-1} < P_{lowerEnv,k}\right)$$

$$\Delta P_{EFR\max,k} = t_{sR} * \begin{cases} dP_{overdeliv\_ramp\_rate} & if \quad f_{overdeliv,k} = 1 \\ dP_{ramp\_rate} & else \end{cases}$$

$$P_{resp,k} = \max\left(\min\left(P_{temp1,k}, P_{EFR,k-1} + \Delta P_{EFR\max,k}\right), P_{EFR,k-1} - \Delta P_{EFR\max,k}\right)$$

$$P_{EFR,k} = \min\left(\max\left(P_{resp,k}, \frac{3600}{t_{sR}}\left(E_{charge,k-1} - E_{EFRul}\right)\right), \frac{3600}{t_{sR}}\left(E_{charge,k-1} - E_{EFRll}\right)\right)$$

$$E_{EFR,k} = E_{EFR,k-1} + \begin{cases} \max\left(-\frac{P_{EFR,k}}{3600\eta_{dis}}, E_{EFR,k-1} - E_{EFRll}\right) & if \quad P_{EFR,k} > 0 \ \&\ E_{EFR,k-1} > E_{EFRll} \\ \min\left(-\frac{\eta_{ch} P_{EFR,k}}{3600}, E_{EFRul} - E_{EFR,k-1}\right) & if \quad P_{EFR,k} < 0 \ \&\ E_{EFR,k-1} < E_{EFRul} \\ 0 & else \end{cases}$$

where

$LUT_{eqv\_curve,upperEnv,lowerEnv}$ = Lookup table data for EFR centre curve and upper and lower envelopes [Hz, MW]

$f_{helping}$ = Flag indicating whether the Frequency error is small [Boolean]

$f_{overdeliv}$ = Flag indicating whether current EFR response is above or below the envelope [Boolean]

dP_{ramp_rate} = Ramp rate limit when not over-delivering, i.e. when ‘below’ the Low envelope [MW/s]

$dP_{overdel\_ramp\_rate}$ = Ramp rate limit when over-delivering, i.e. when ‘above’ the Low envelope [MW/s]

ΔP_{EFRmax} = Ramp rate limit [MW]

E_{EFR} = Energy charge [MWh]

$E_{EFRll,ul}$ = Energy charge lower and upper limits [MWh]

η_{dis} = EFR unit discharge efficiency [-]

η_{ch} = EFR unit charge efficiency [-]

Other variables: Intermediate help variables [var]

3.2.4 Firm Frequency Response

The structure of the Firm Frequency Response (FFR) model is identical to the Interconnector model in Section 3.2.5. Only the numerical parameter values differ.

$$w_{e,k} = w_n - w_{k-k_{delFFR}}$$

$$P_{pu1,k} = \begin{cases} \min\left(\left(w_{e,k} + w_{1FFR}\right) / \left(w_{2FFR} - w_{1FFR}\right), 1\right) & if \quad w_{e,k} < -w_{1FFR} \\ 0 & if \quad -w_{1FFR} \le w_{e,k} \le w_{1FFR} \\ \max\left(\left(w_{e,k} - w_{1FFR}\right) / \left(w_{2FFR} - w_{1FFR}\right), 1\right) & if \quad w_{1FFR} < w_{e,k} \end{cases}$$

$$P_{pu2,k} = \begin{cases} P_{pu1,k-1} - t_{sR} / t_{PFFR} & if \quad P_{pu1,k} < P_{pu1,k-1} - t_{sR} / t_{PFFR} \\ P_{pu1,k} & if \quad P_{pu1,k-1} - t_{sR} / t_{PFFR} \le P_{pu1,k} \le P_{pu1,k-1} + t_{sR} / t_{PFFR} \\ P_{pu1,k-1} + t_{sR} / t_{PFFR} & if \quad P_{pu1,k-1} - t_{sR} / t_{PFFR} < P_{pu1,k} \end{cases}$$

$$P_{FFR,k} = P_{FFRvol} P_{pu2,k}$$

where

w_{1FFR} = Frequency deadband [Hz]

w_{2FFR} = Frequency at full volume [Hz]

$P_{pu1,2}$ = Intermediate per-unit response variables [-]

t_{PFFR} = Ramp time [s]

P_{FFRvol} = Volume [MW]

3.2.5 Interconnector

The (BritNed) interconnector is modelled as a proportional gain of response power against Frequency deviation, with a deadband of 0.015 Hz around 50 Hz and a limit at the maximum volume (symmetric around 0 MW) of the interconnector.

$$w_{e,k} = w_n - w_{k-k_{delIC}}$$

$$P_{pu1,k} = \begin{cases} \min\left(\left(w_{e1,k} + w_{1IC}\right) / \left(w_{2IC} - w_{1IC}\right), 1\right) & if \quad w_{e1,k} < -w_{1IC} \\ 0 & if \quad -w_{1IC} \le w_{e1,k} \le w_{1IC} \\ \max\left(\left(w_{e1,k} - w_{1IC}\right) / \left(w_{2IC} - w_{1IC}\right), 1\right) & if \quad w_{1IC} < w_{e1,k} \end{cases}$$

$$P_{pu2,k}=\begin{cases} P_{pu1,k-1}-t_{sR}/t_{PIC} & if \quad P_{pu1,k}<P_{pu1,k-1}-t_{sR}/t_{PIC} \\ P_{pu1,k} & if \quad P_{pu1,k-1}-t_{sR}/t_{PIC}\le P_{pu1,k}\le P_{pu1,k-1}+t_{sR}/t_{PIC} \\ P_{pu1,k-1}+t_{sR}/t_{PIC} & if \quad P_{pu1,k-1}-t_{sR}/t_{PIC}<P_{pu1,k} \end{cases}$$

$$P_{IC,k}=P_{ICvol}P_{pu2,k}$$

where

w_{1IC} = Frequency deadband [Hz]

w_{2IC} = Frequency at full volume [Hz]

$P_{pu1,2}$ = Intermediate per-unit response variables [-]

t_{PIC} = Ramp time [s]

P_{ICvol} = Volume [MW]

3.2.6 Dynamic Containment

In principle, Dynamic Containment (DC) is modelled in a similar way to the Interconnector, as a proportional gain of response power against Frequency deviation over its main operating range, with a deadband on Frequency. However, DC has another 'creep' proportionality region between deadband and main operating range. This combination of factors is modelled (in Simulink) as a lookup table (LUT) with linear interpolation between the defined LUT points.

$$w_{e,k}=w_n-w_{k-k_{delDC}}$$

$$P_{pu1,k}=LUT_{DC}(w_{e1,k})$$

$$P_{pu2,k}=\begin{cases} P_{pu1,k-1}-t_{sR}/t_{PDC} & if \quad P_{pu1,k}<P_{pu1,k-1}-t_{sR}/t_{PDC} \\ P_{pu1,k} & if \quad P_{pu1,k-1}-t_{sR}/t_{PDC}\le P_{pu1,k}\le P_{pu1,k-1}+t_{sR}/t_{PDC} \\ P_{pu1,k-1}+t_{sR}/t_{PDC} & if \quad P_{pu1,k-1}-t_{sR}/t_{PDC}<P_{pu1,k} \end{cases}$$

$$P_{DC,k}=P_{DCvol}P_{pu2,k}$$

In addition, the DC energy charge is calculated, based on the DC response power and the charge/discharge-dependent efficiency. In the present Simulink model, DC charge is monitored but DC response is not restricted if the charge limit is reached. However, this can be added easily if/when required.

$$E_{DC,k}=E_{DC,k-1}+\begin{cases} \max(-\frac{P_{DC,k}}{3600\eta_{dis}},E_{DC,k-1}-E_{DCll}) & if \quad P_{DC,k}>0\ \&\ E_{DC,k-1}>E_{DCll} \\ \min(-\frac{\eta_{ch}P_{DC,k}}{3600},E_{DCul}-E_{DC,k-1}) & if \quad P_{DC,k}<0\ \&\ E_{DC,k-1}<E_{DCul} \\ 0 & else \end{cases}$$

where

LUT_{DC} = Lookup table data response power vs. Frequency [Hz, MW]

$P_{pu1,2}$ = Intermediate per-unit response variables [-]

t_{PDC} = Ramp time [s]

P_{DCvol} = Volume [MW]

E_{DC} = Energy charge [MWh]

$E_{DCll,ul}$ = Energy charge lower and upper limits [MWh]

η_{dis} = DC unit discharge efficiency [-]

η_{ch} = DC unit charge efficiency [-]

3.2.7 Dynamic Modulation

The structure of the Dynamic Modulation (DM) model is identical to the DC model. Only the numerical parameter values differ.

$$w_{e,k} = w_n - w_{k-k_{delDM}}$$

$$P_{pu1,k} = LUT_{DM}(w_{e1,k})$$

$$P_{pu2,k} = \begin{cases} P_{pu1,k-1} - t_{sR} / t_{PDM} & if \quad P_{pu1,k} < P_{pu1,k-1} - t_{sR} / t_{PDM} \\ P_{pu1,k} & if \quad P_{pu1,k-1} - t_{sR} / t_{PDM} \le P_{pu1,k} \le P_{pu1,k-1} + t_{sR} / t_{PDM} \\ P_{pu1,k-1} + t_{sR} / t_{PDM} & if \quad P_{pu1,k-1} - t_{sR} / t_{PDM} < P_{pu1,k} \end{cases}$$

$$P_{DM,k} = P_{DMvol} P_{pu2,k}$$

$$E_{DM,k} = E_{DM,k-1} + \begin{cases} \max(-\frac{P_{DM,k}}{3600\eta_{dis}}, E_{DM,k-1} - E_{DMll}) & if \quad P_{DM,k} > 0 \,\&\, E_{DM,k-1} > E_{DMll} \\ \min(-\frac{\eta_{ch} P_{DM,k}}{3600}, E_{DMul} - E_{DM,k-1}) & if \quad P_{DM,k} < 0 \,\&\, E_{DM,k-1} < E_{DMul} \\ 0 & else \end{cases}$$

where

LUT_{DM} = Lookup table data response power vs. Frequency [Hz, MW]

$P_{pu1,2}$ = Intermediate per-unit response variables [-]

t_{PDM} = Ramp time [s]

P_{DMvol} = Volume [MW]

E_{DM} = Energy charge [MWh]

$E_{DMll,ul}$ = Energy charge lower and upper limits [MWh]

η_{dis} = DM unit discharge efficiency [-]

η_{ch} = DM unit charge efficiency [-]

3.2.8 Dynamic Regulation

The structure of the Dynamic Regulation (DR) model is identical to the DC and DM models. Only the numerical parameter values differ.

$$w_{e,k} = w_n - w_{k-k_{delDR}}$$

$$P_{pu1,k} = LUT_{DR}(w_{e1,k})$$

$$P_{pu2,k} = \begin{cases} P_{pu1,k-1} - t_{sR} / t_{PDR} & if \quad P_{pu1,k} < P_{pu1,k-1} - t_{sR} / t_{PDR} \\ P_{pu1,k} & if \quad P_{pu1,k-1} - t_{sR} / t_{PDR} \le P_{pu1,k} \le P_{pu1,k-1} + t_{sR} / t_{PDR} \\ P_{pu1,k-1} + t_{sR} / t_{PDR} & if \quad P_{pu1,k-1} - t_{sR} / t_{PDR} < P_{pu1,k} \end{cases}$$

$$P_{DR,k} = P_{DRvol} P_{pu2,k}$$

$$E_{DR,k} = E_{DR,k-1} + \begin{cases} \max(-\frac{P_{DR,k}}{3600\eta_{dis}}, E_{DR,k-1} - E_{DRll}) & if \quad P_{DR,k} > 0 \;\&\; E_{DR,k-1} > E_{DRll} \\ \min(-\frac{\eta_{ch} P_{DR,k}}{3600}, E_{DRul} - E_{DR,k-1}) & if \quad P_{DR,k} < 0 \;\&\; E_{DR,k-1} < E_{DRul} \\ 0 & else \end{cases}$$

where

LUT_{DR} = Lookup table data response power vs. Frequency [Hz, MW]

$P_{pu1,2}$ = Intermediate per-unit response variables [-]

t_{PDR} = Ramp time [s]

P_{DRvol} = Volume [MW]

E_{DR} = Energy charge [MWh]

$E_{DRll,ul}$ = Energy charge lower and upper limits [MWh]

η_{dis} = DR unit discharge efficiency [-]

η_{ch} = DR unit charge efficiency [-]

4 Simulink Simulation Test Results

The detailed results of the validation of the Simulink model against the ShinyAppLegacy are shown in Appendix B, in graphical form. The results correspond closely in all test cases. Any minor numerical differences are, most likely, the result of different simulation integration routines. For example, the ShinyAppLegacy is fully discretised and uses a fixed simulation step size (user-adjustable and 0.01 s by default), whereas the Simulink model is partly continuous-time, albeit with discretised elements (potentially with different time steps, although all 0.01 s by default), and uses a variable-step integration algorithm.

5 Potential Model Improvements

The following issues have been identified as potential improvements to be made to the current model as part of Task 2.3 of Phase 2 of the 'DM/DR Evaluation and Development' project.

5.1 Improvements Relative to ShinyAppLegacy

The following issues of the ShinyAppLegacy model were identified during the Simulink model development and validation as requiring, or at least benefitting from, further development of the current ShinyAppLegacy model.

PSH Dynamic Response

The transitions from P to S and from S to 0 (or H) show some unrealistic characteristics. This issue had already been identified by the main ShinyAppLegacy developer, W. Dale. If data or general information about such more realistic behaviour is available, this will be incorporated in the Simulink model.

Triggered/Static

The Triggered/Static response in ShinyAppLegacy stays on once it has been triggered on; there is no mechanism to switch it off again. Whilst that is realistic during the short 60-s simulations of sudden Loss changes, Triggered/Static response might be triggered and then switched off again during the longer (typically one hour) simulation runs that are planned to test DM/DR behaviour.

However, if it is certain (or assured) that Triggered/Static response won't be used in any of the simulation scenarios for DM/DR assessment, it may not be necessary to make this change to the Triggered/Static response model.

EFR

Like the Triggered/Static response mentioned above, EFR does not appear to be switched 'off' once it has been triggered/started. Furthermore, there appears to be some doubt about the correctness of the switching between the upper and lower envelopes in the comments in the ShinyAppLegacy C++ code. In the Loss step scenarios the EFR response varies little or not at all between the envelopes. The Simulink model's EFR operation needs to be tested with more complex test signals/scenarios (e.g. representing wind-power variations) over a longer period, with a requirement for both positive and negative EFR, to check its correctness.

5.2 Other Enhancements

Prefault Parameters

The ShinyAppLegacy has options to start a simulation run with two or more types of initial condition:

- Set frequency
- Set imbalance
- Possibly others

The Simulink model was set up and validated with the first option 'set frequency' (with 50 Hz) only. If other prefault parameter options such as 'set imbalance' are required for the Simulink model, the required (steady-state, pre-simulation) calculations would need to be added.

Linearisation

Most FRS models are suitable for linearisation, for the linear analysis of stability properties, e.g. the calculation of gain and phase margins and the display of Bode or Nichols plots. However, the linearization of some models, e.g. EFR, still needs to be checked.

Simulation User-Friendliness

The simulation can be made more user-friendly, for example by providing flags to switch FRS services off instead of the current method of setting the corresponding volume to 0.

6 Conclusions

The Simulink model that has been developed includes all FRS services that are represented in the FFSE ShinyAppLegacy model, including PSH Response, EFR, FFR, Interconnector, Static Response and DC. The Simulink model was validated against the ShinyAppLegacy model through comparison of the graphical simulation outputs.

The issues that will be addressed next in the project, in Task 2.3, are listed and discussed in Section 5.

References

[1] G. M. van der Molen, *FFSE Modelling, Simulation & Optimisation: Improvements & Recommendations; Deliverable 1e – Task 1.3: Required DM/DR Services & Test Scenarios*, Project report d002v01, 23 March 2021.

[2] A. Sims, W. Ramsay and L. Blaxland, *Faster Acting Response*, https://www.nationalgrideso.com/document/119256/download, accessed 16/3/2021, July 2018.

[3] ISC, *Review and Analysis of Software for Dynamic Moderation and Dynamic Regulation Services – Phase 2*, ISC document p20210603, 3 June 2021.

[4] National Grid, *Enhanced Frequency Response: Invitation to tender for pre-qualified parties*, National Grid document, v2.2, 8 July 2012.

[5] Wikipedia, *Swing equation*, website https://en.wikipedia.org/wiki/Swing_equation, accessed 30/6/2021.

Appendix A: FFSE Settings for Validation

1 Simulation Settings

Validation simulation scenarios

All validation test scenarios used a (imbalance) Loss step change, with (prefault) steady-state conditions with perfect balance preceding the Loss change. This corresponds to the 'set frequency' option in the 'Options' tab of ShinyAppLegacy.

Simulation run time

The simulations were set to run for 60 s following the Loss step change, preceded by 2 or 10 s (ShinyAppLegacy) or 10 s (Simulink) to check on steady-state behaviour before the step change. In ShinyAppLegacy, the step change happens at exactly 0 s (by default; any adjustment requires editing of R code), with the preceding (steady-state) time being shown as negative time and the end time being 60 s. In Simulink, the simulation always starts at 0 s so that the step change occurs at 10 s and the end time is 70 s.

Simulink solver

The Simulink solver was selected as a 'Variable step' type, with 'auto' solver selection. The latter was normally selected (automatically) as 'ode23t'. The minimum time step was selected as 'auto'. All other solver settings were kept at their default values.

2 Grid System Parameters

The following values or volumes were used as default or initial values for the validation of the Simulink model against the FFSE ShinyAppLegacy model. A step change was used to represent Loss/Imbalance. Note: because the various services were tested in isolation, the volumes used here were larger than they would normally be, in combination with other services.

- Demand: 1000 MW
- Grid Inertia: 112,000 MVA.s
- Loss/Imbalance: -1,000 MW

3 FRS Parameters

The FRS parameters are listed in the individual sections in Appendix B below.

Appendix B: Validation Results

1 Grid System Without FRS

Simulation scenario parameters

Loss: -1,000 MW

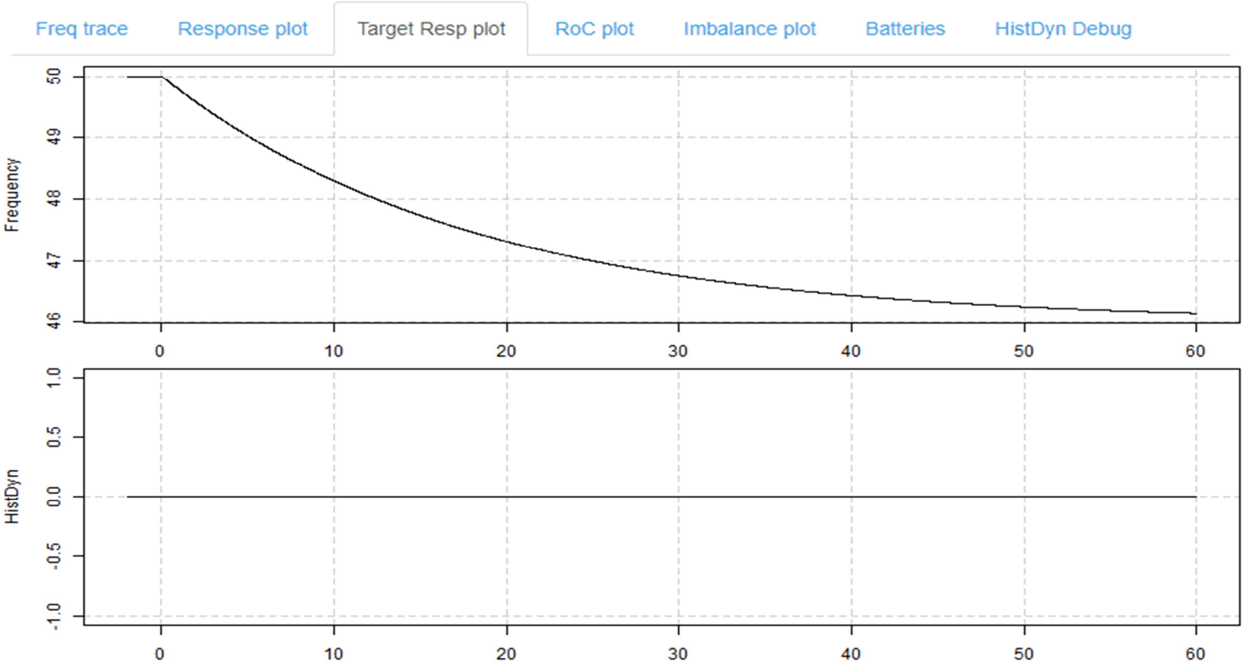

Figure 2: ShinyAppLegacy Output

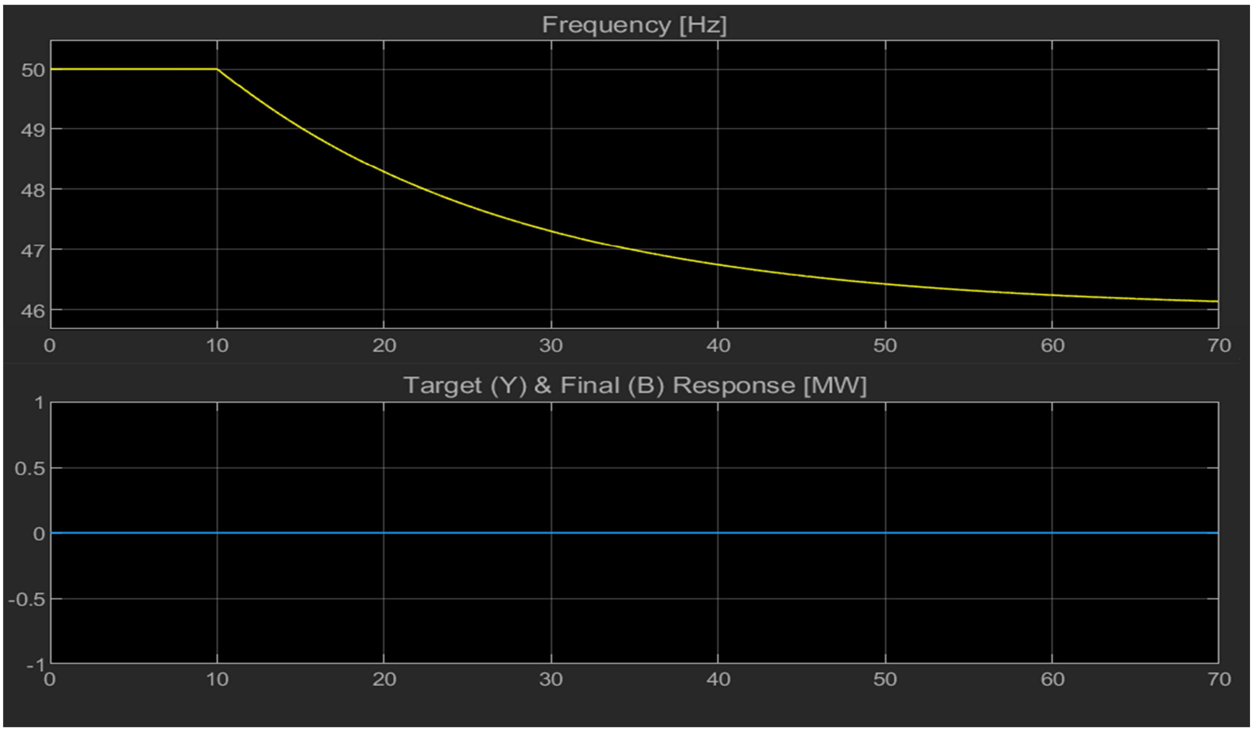

Figure 3: Simulink Output

2 PSH Dynamic Response - P

Simulation scenario parameters

Loss: -1,000 MW

FRS parameters

Max P Dynamic Response: 1,200 MW

P delay/lag: 1.5 s

P delivery time: 10 s

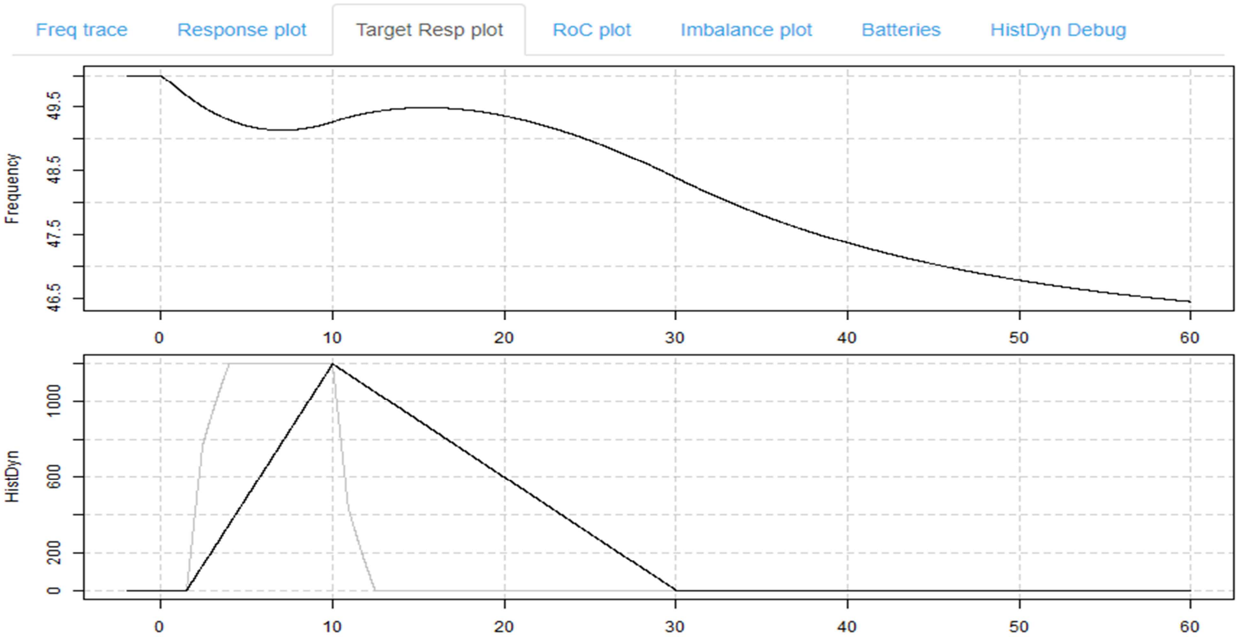

Figure 4: ShinyAppLegacy Output

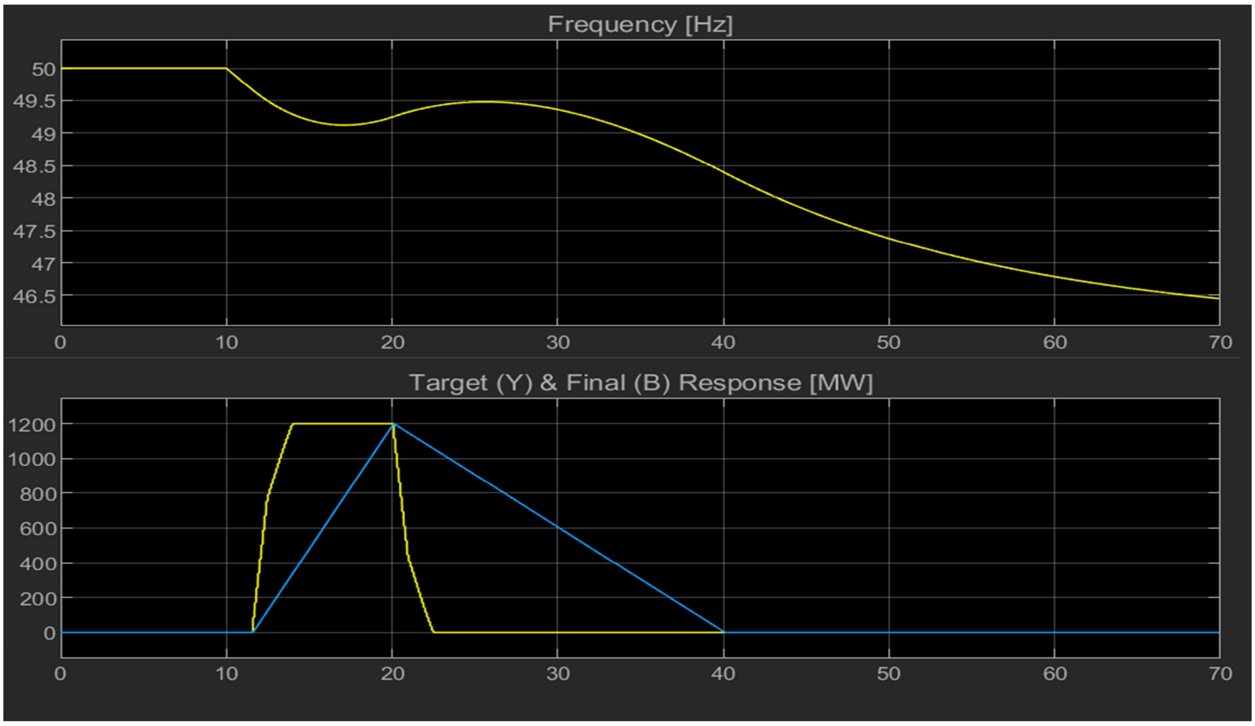

Figure 5: Simulink Output

3 PSH Dynamic Response - PS

Simulation scenario parameters

Loss: -1,000 MW

FRS parameters

Max P Dynamic Response: 600 MW

P delay/lag: 1.5 s

P delivery time: 10 s

S Dynamic Response: 1,200 MW

S delay/lag: 10 s

S delivery time: 30 s

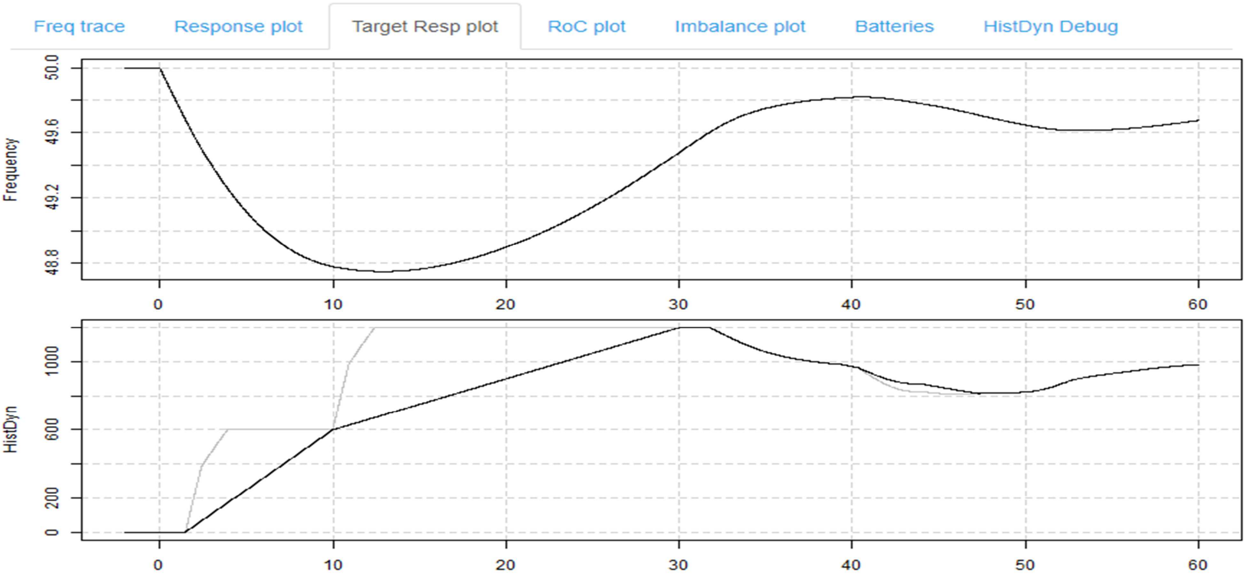

Figure 6: ShinyAppLegacy Output

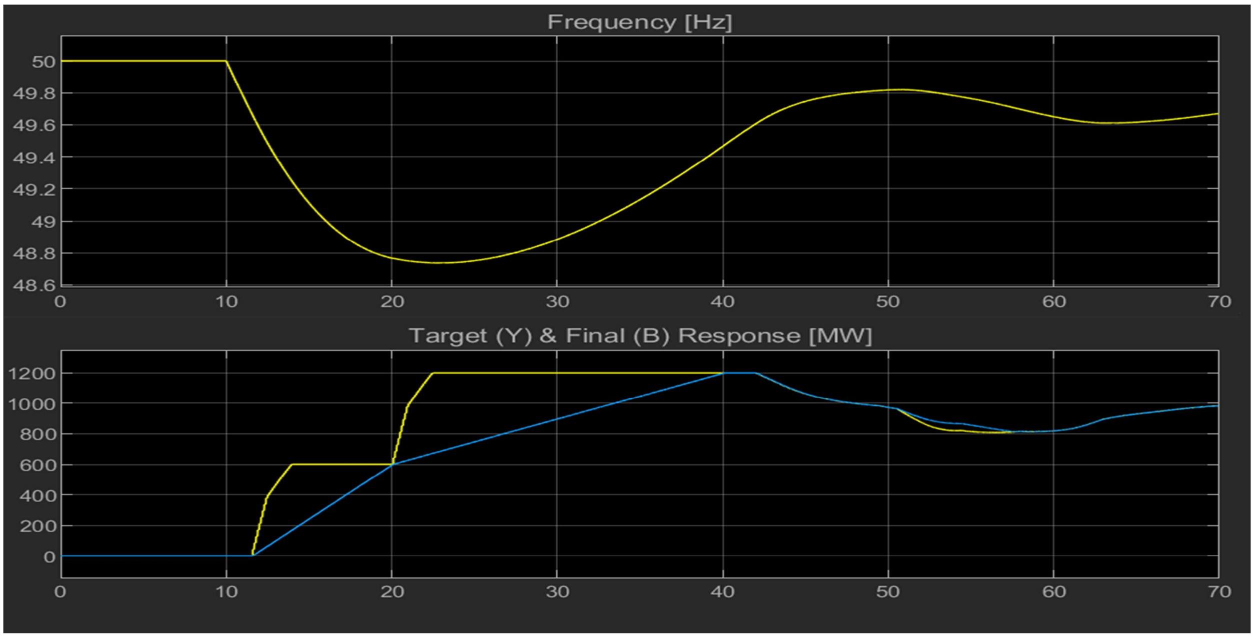

Figure 7: Simulink Output

4 PSH Dynamic Response - H

Simulation scenario parameters

Loss: +1,000 MW

FRS parameters

Max PH Dynamic Response: ±1,200 MW

PH delay/lag: 1.5 s

PH delivery time: 10 s

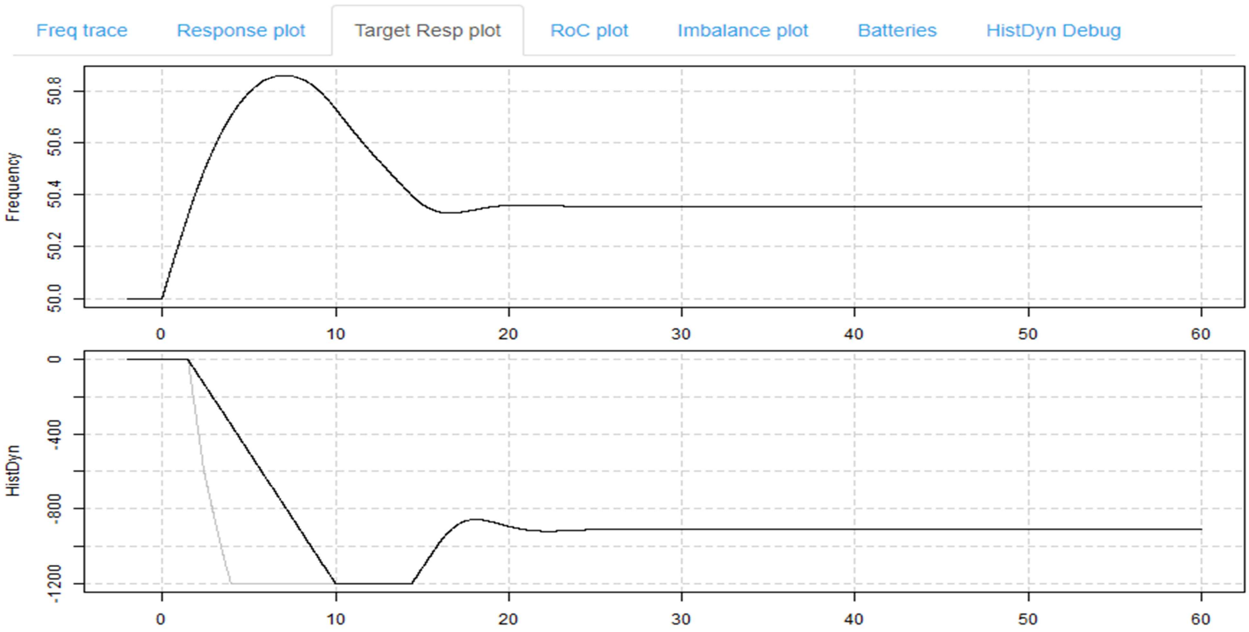

Figure 8: ShinyAppLegacy Output

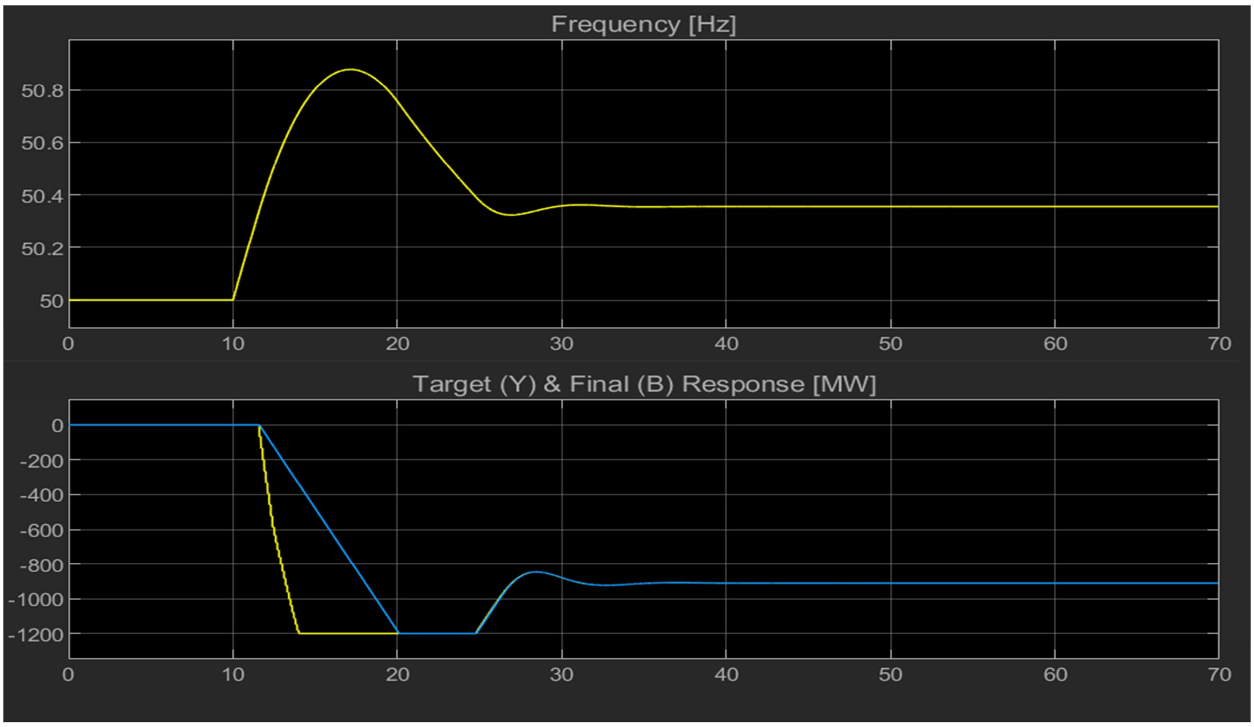

Figure 9: Simulink Output

5 PSH Static Response

Simulation scenario parameters

Loss: -300 MW

FRS parameters

Static 1: 100 MW at 0.3 Hz

Static 2: 200 MW at 0.5 Hz

Static delay/lag: 1.5 s

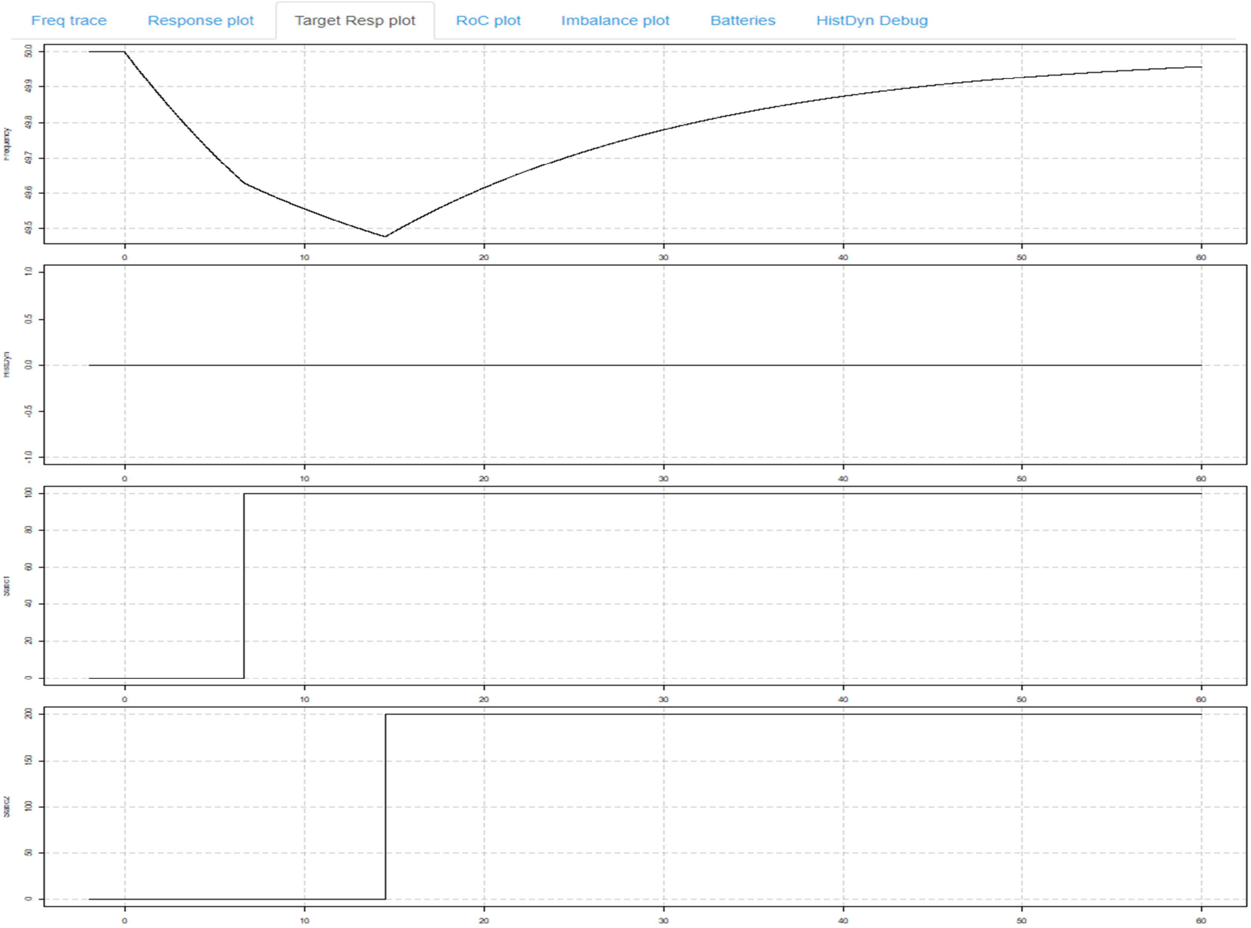

Figure 10: ShinyAppLegacy Output

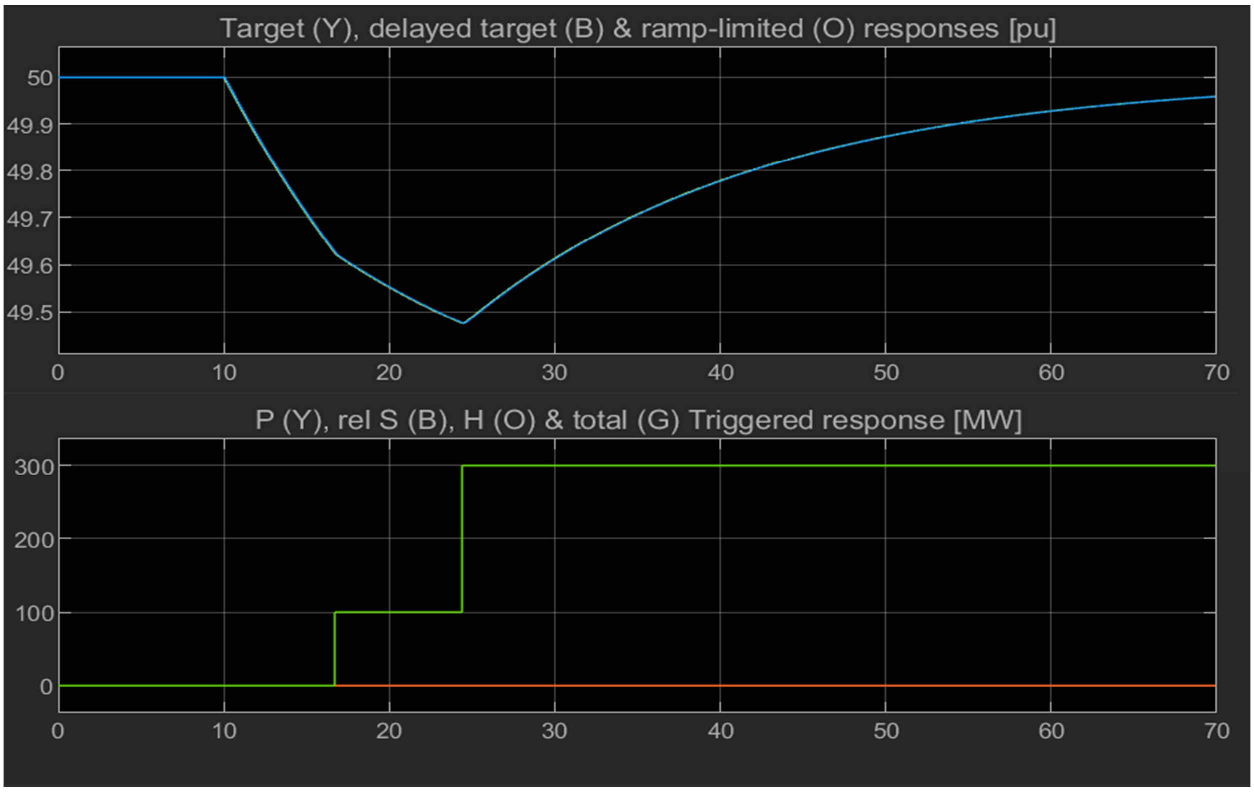

Figure 11: Simulink Output

6 EFR

Combination of PSH Dynamic Response and EFR.

Simulation scenario parameters

- Loss: -1,000 MW

PSH Dynamic Response parameters

- Max P Dynamic Response: 900 MW
- P delay/lag: 1.5 s
- P delivery time: 10 s
- S Dynamic Response: 1,200 MW
- S delay/lag: 10 s
- S delivery time: 30 s

EFR parameters

- EFR Ref max volume: 1,000 MW
- Delay/lag: 0.5 s
- Under-del ramp time: 0.5 s
- Over-del ramp time: 10 s
- In-env ramp time: 100 s

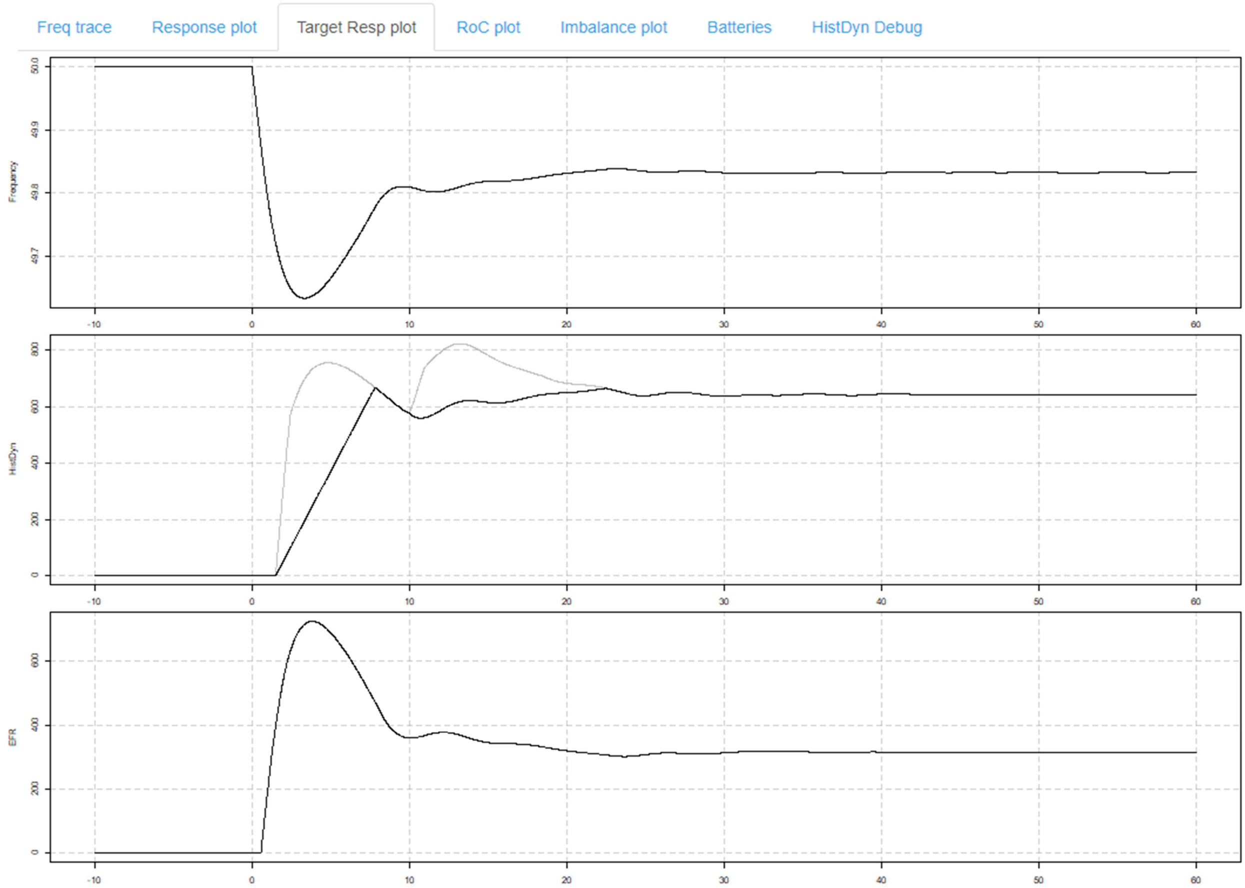

Figure 12: ShinyAppLegacy Output – PSH Dynamic & EFR Response

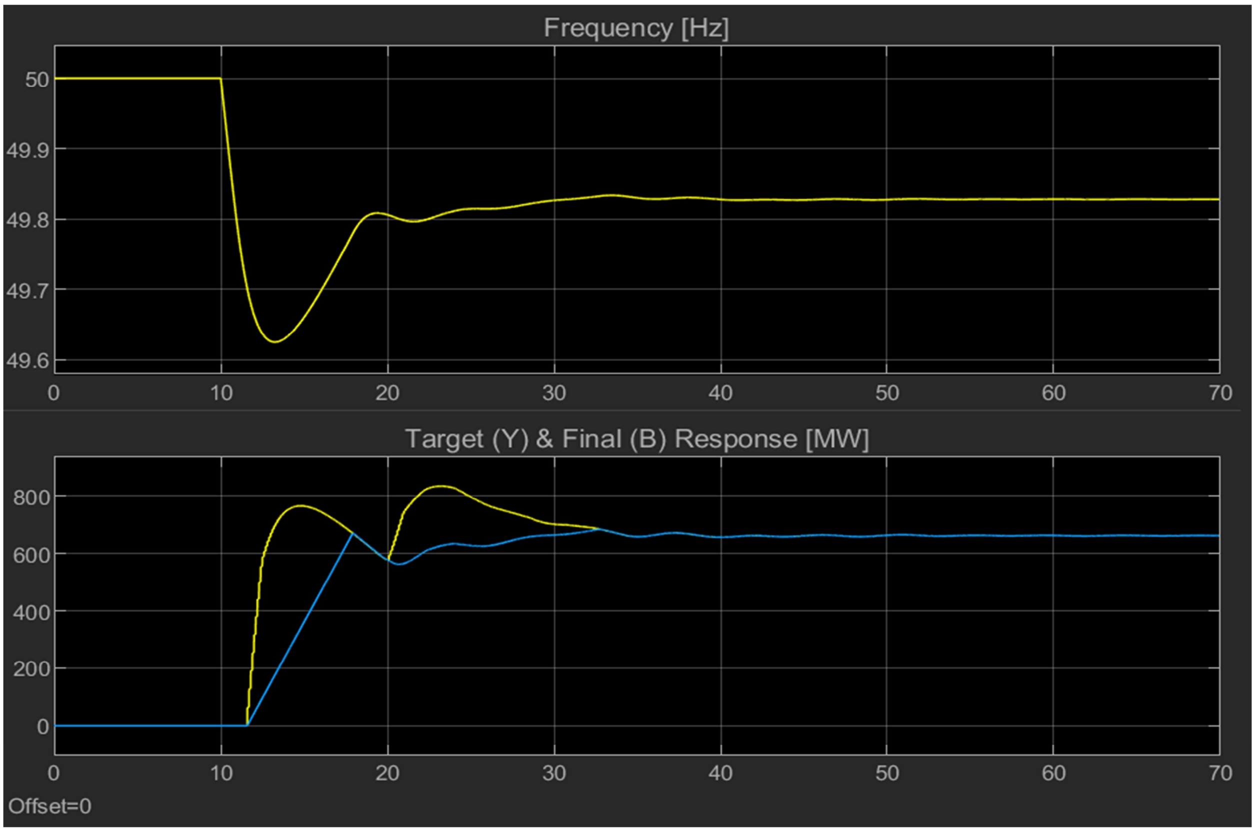

Figure 13: Simulink Output – PSH Dynamic Response

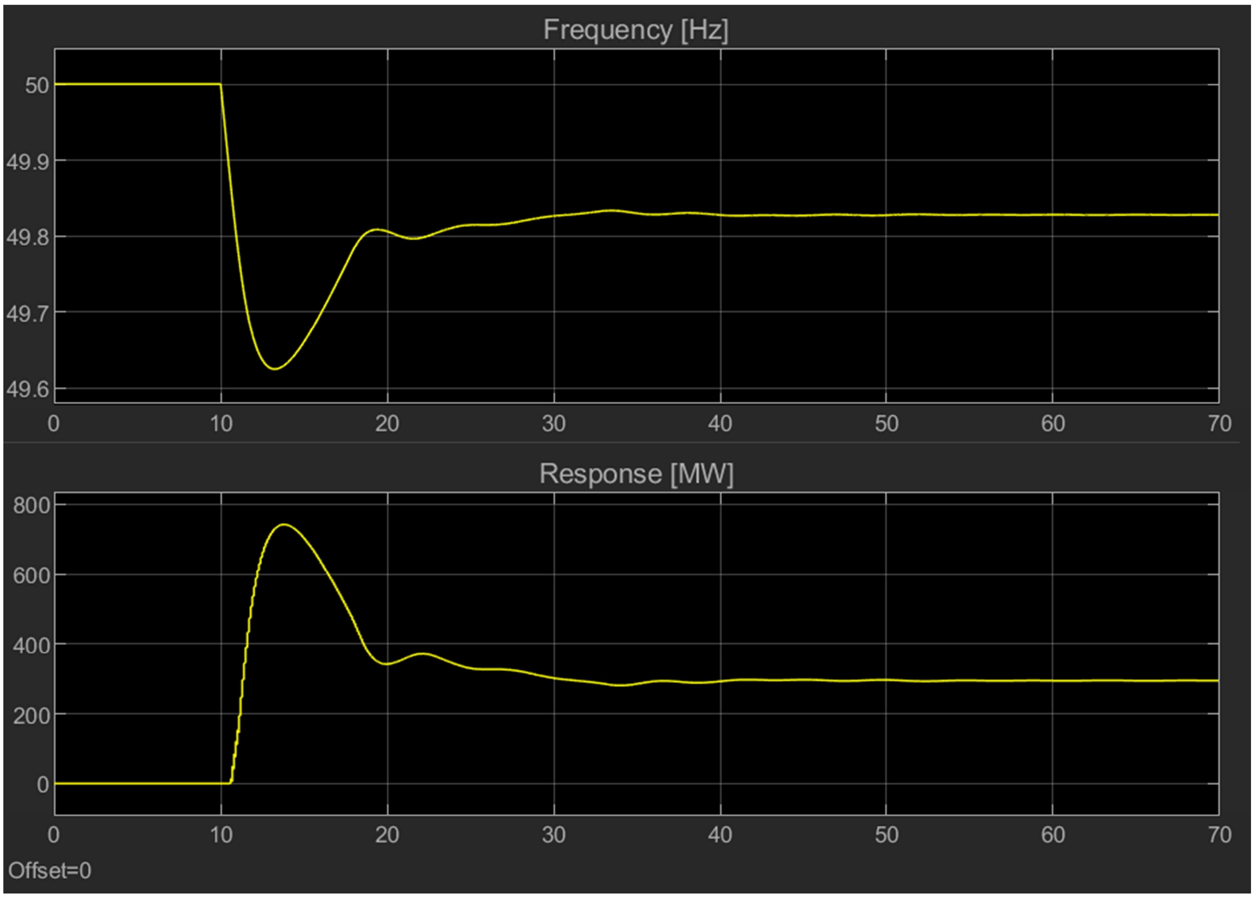

Figure 14: Simulink Output – EFR Response

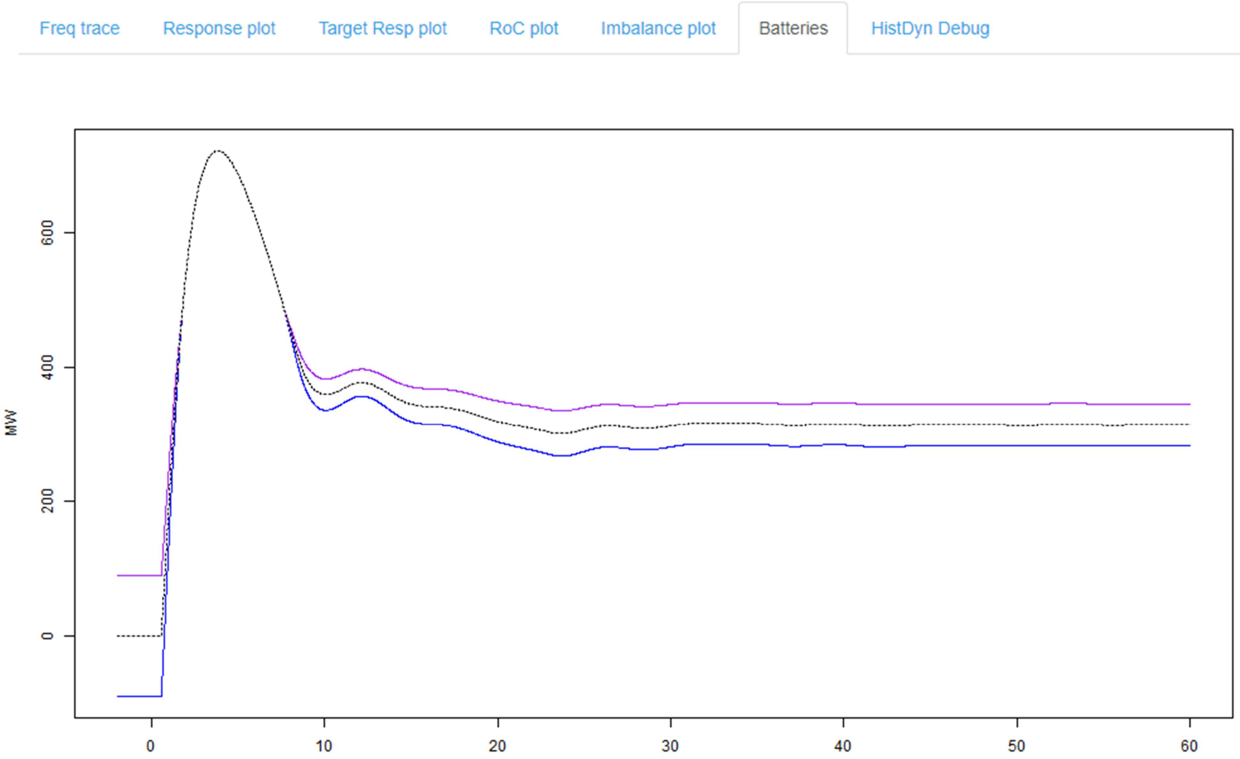

Figure 15: ShinyAppLegacy Output – EFR Envelopes

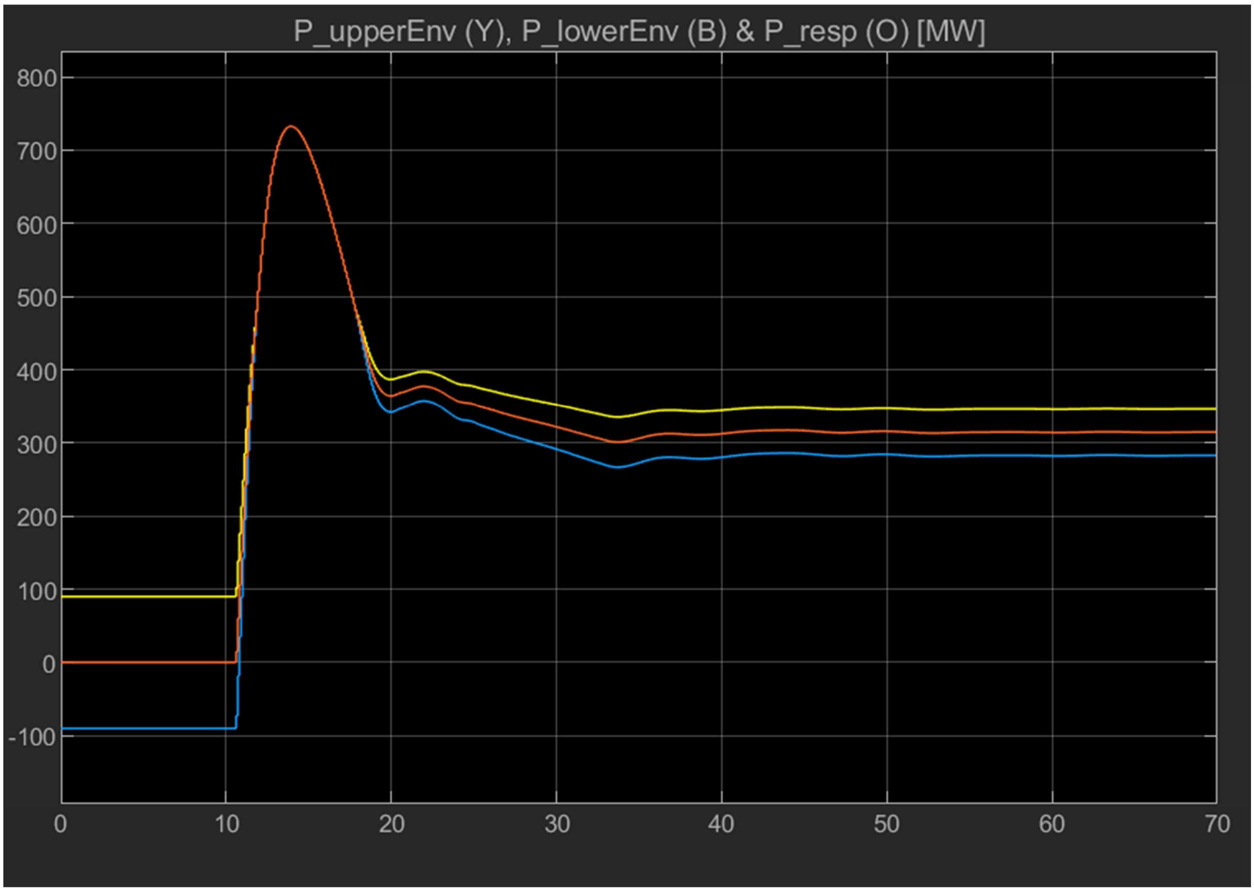

Figure 16: Simulink Output – EFR Envelopes

7 FFR Ref

Simulation scenario parameters

- Loss: -1,000 MW

FRS parameters

- FFR Ref max volume: 1,000 MW
- Delay/lag: 1.5 s
- Delivery time: 10 s

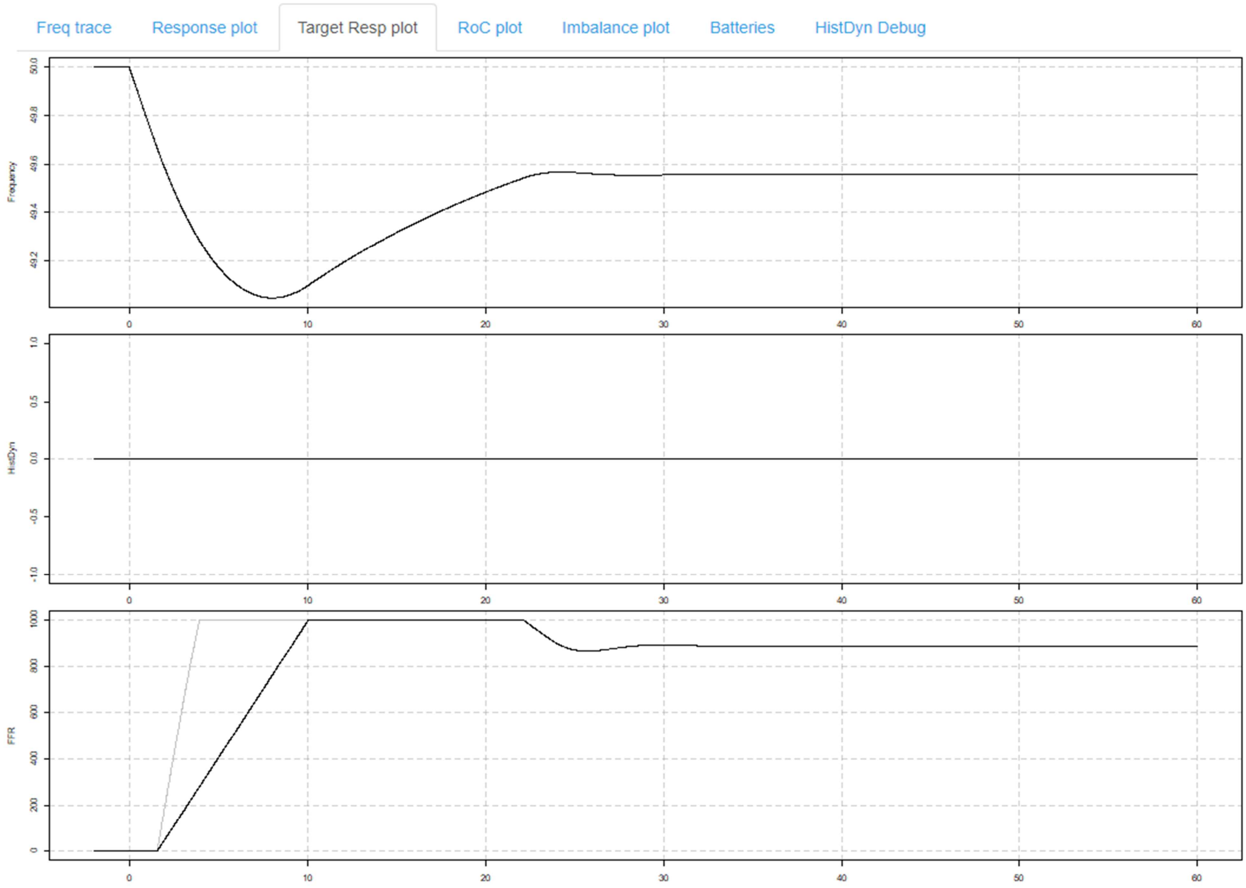

Figure 17: ShinyAppLegacy Output

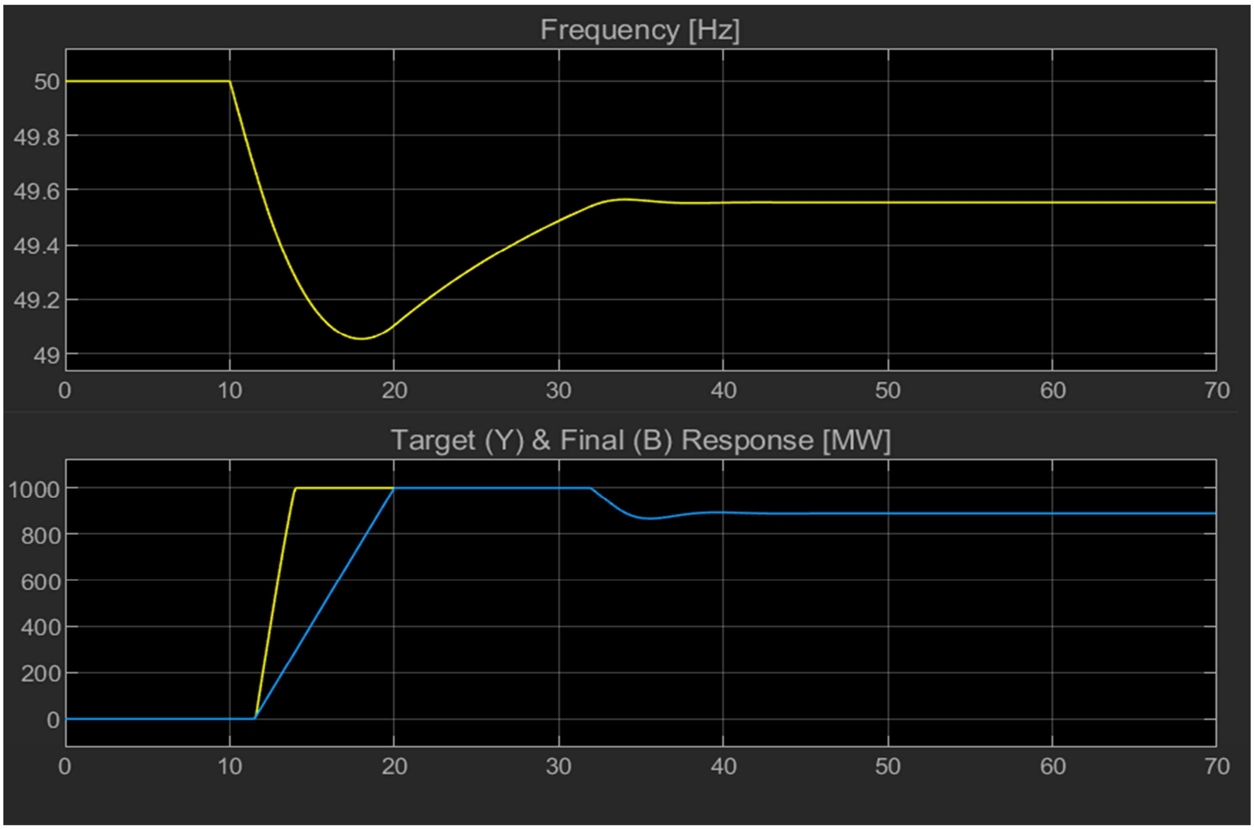

Figure 18: Simulink Output

8 BritNed/Interconnector

Simulation scenario parameters

- Loss: -1,000 MW

FRS parameters

- BritNed/Interconnector max volume: 1,000 MW
- Delay/lag: 1.5 s

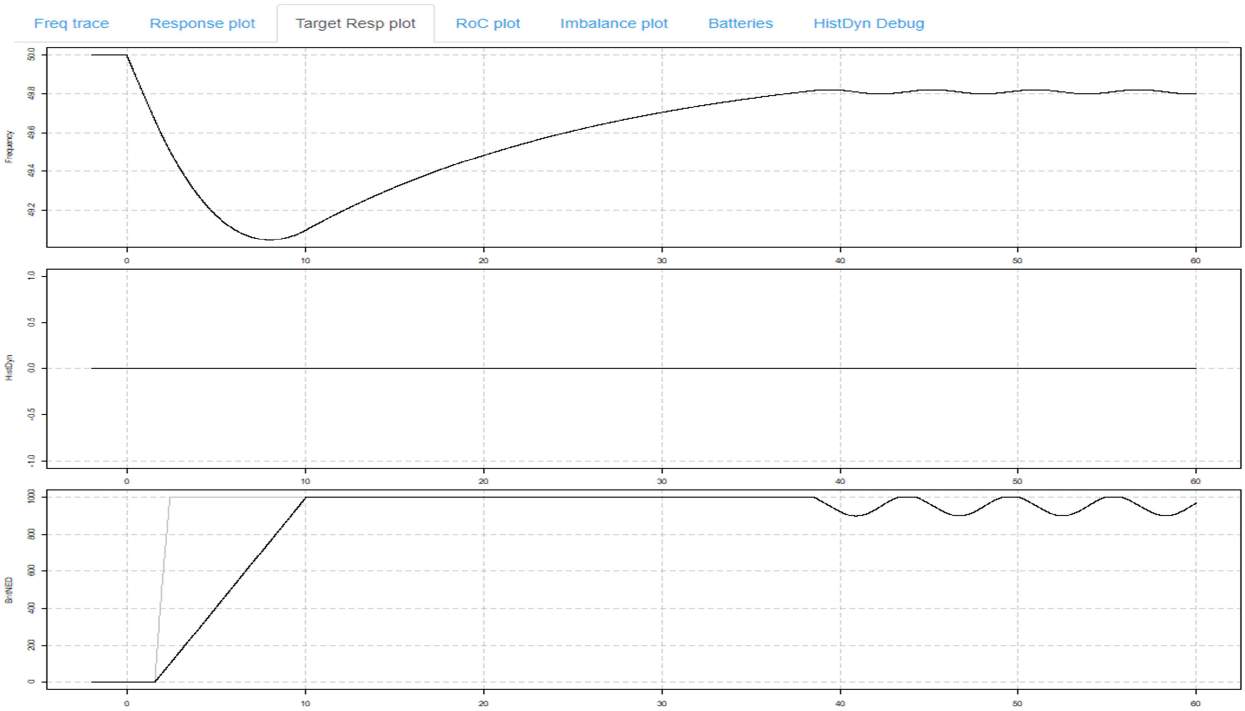

Figure 19: ShinyAppLegacy Output

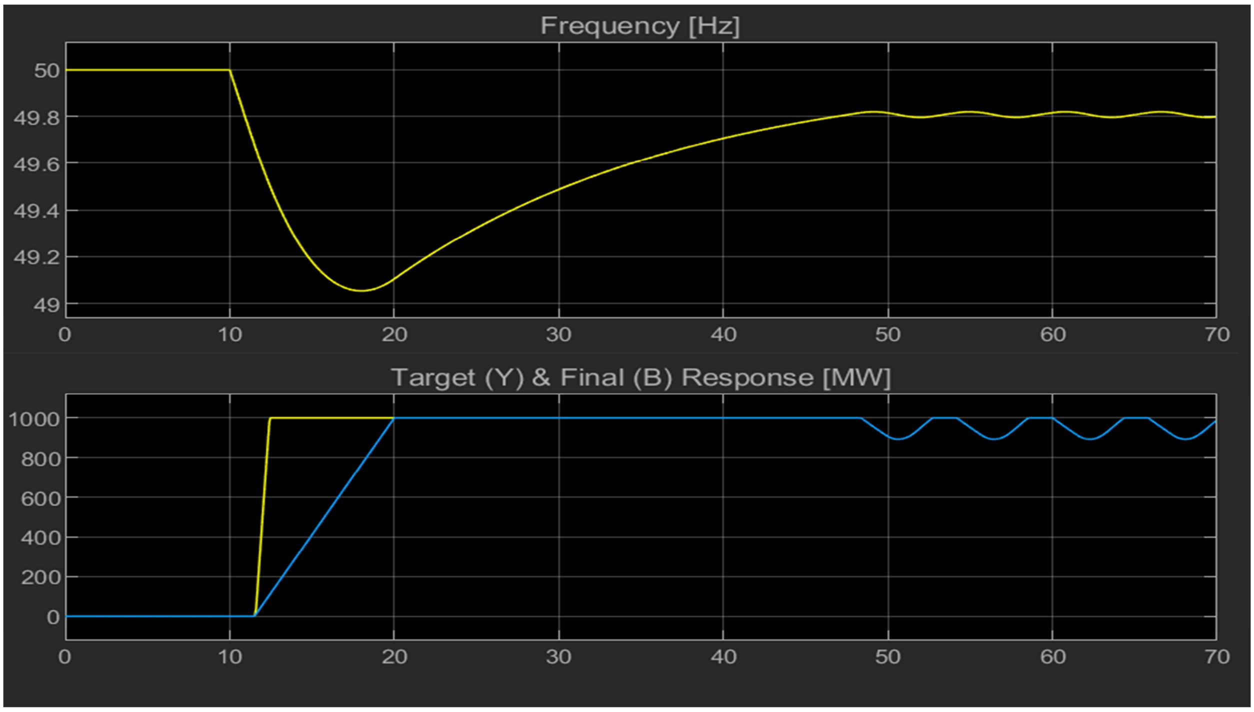

Figure 20: Simulink Output

9 DC

Simulation scenario parameters

- Loss: -1,000 MW

FRS parameters

- DC max volume: 1,000 MW
- Delay/lag: 0.5 s
- Ramp time: 0.5 s
- Creep: 0.05

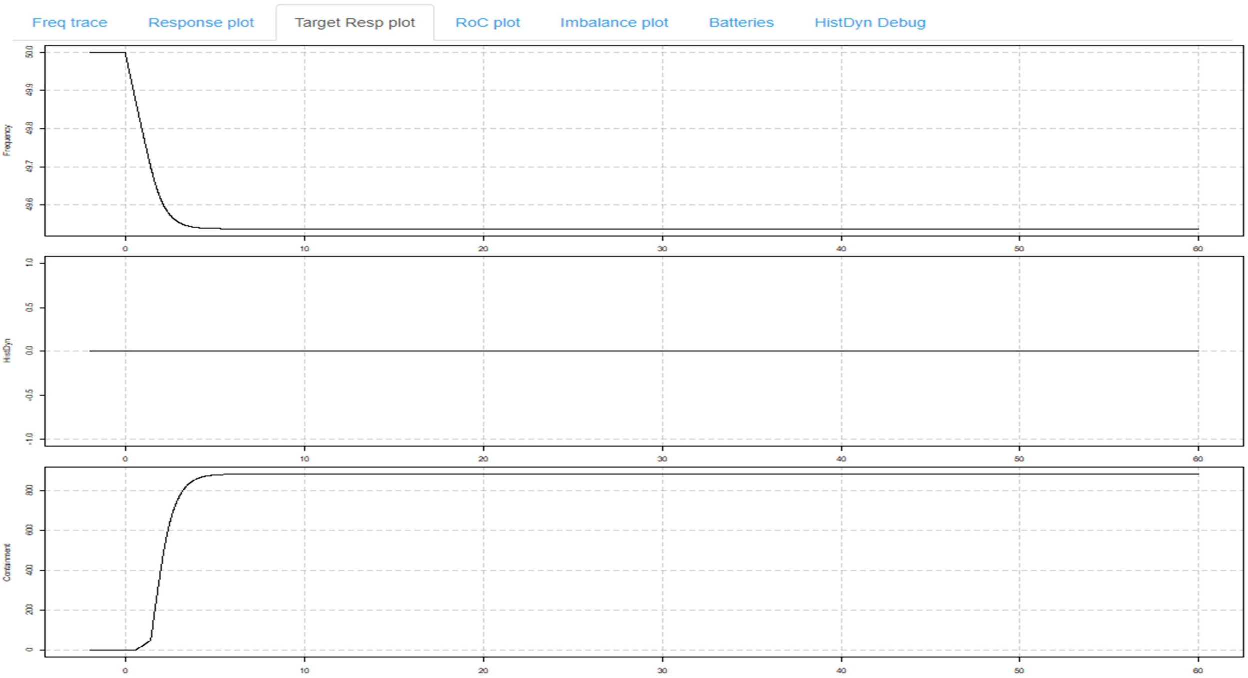

Figure 21: ShinyAppLegacy Output

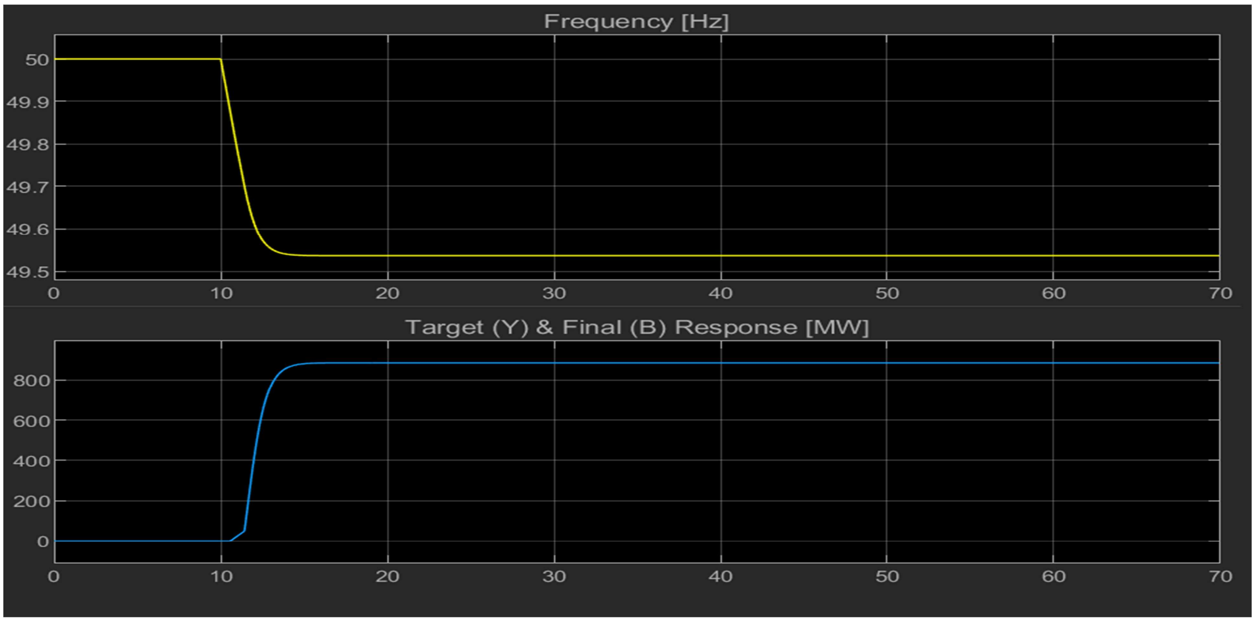

Figure 22: Simulink Output

10 DM

Simulation scenario parameters

- Loss: -1,000 MW

FRS parameters

- DM max volume: 1,000 MW
- Delay/lag: 0.5 s
- Ramp time: 0.5 s
- Creep: 0.05

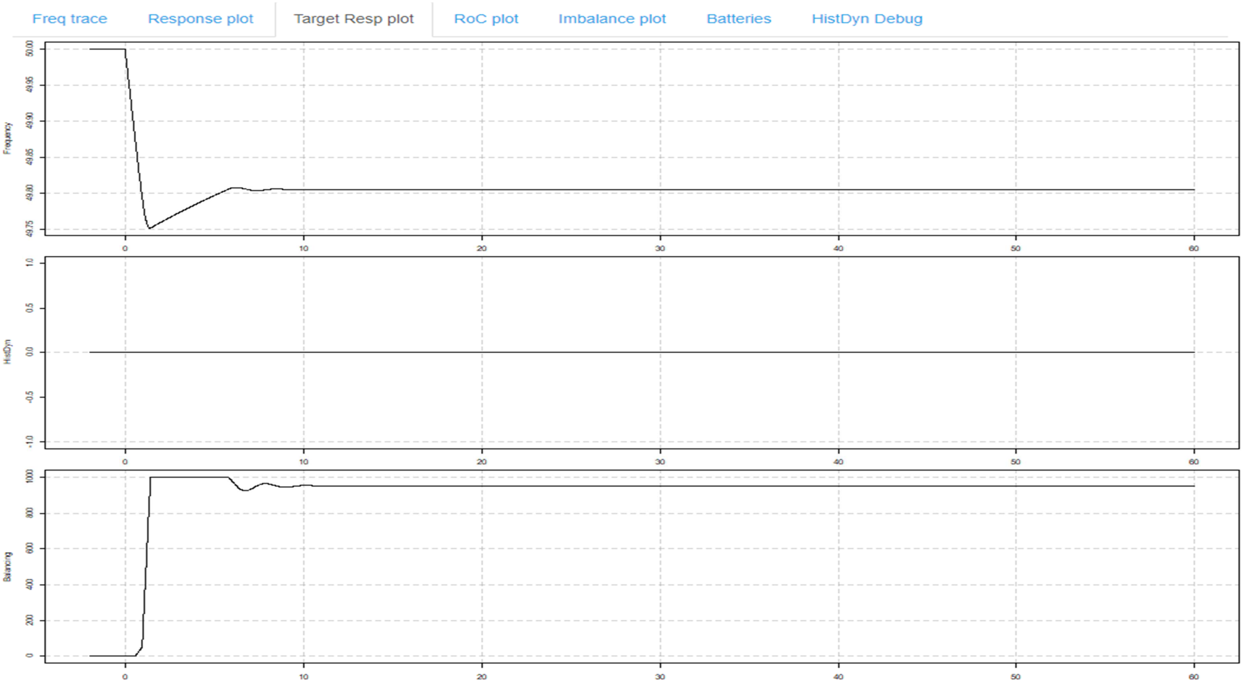

Figure 23: ShinyAppLegacy Output

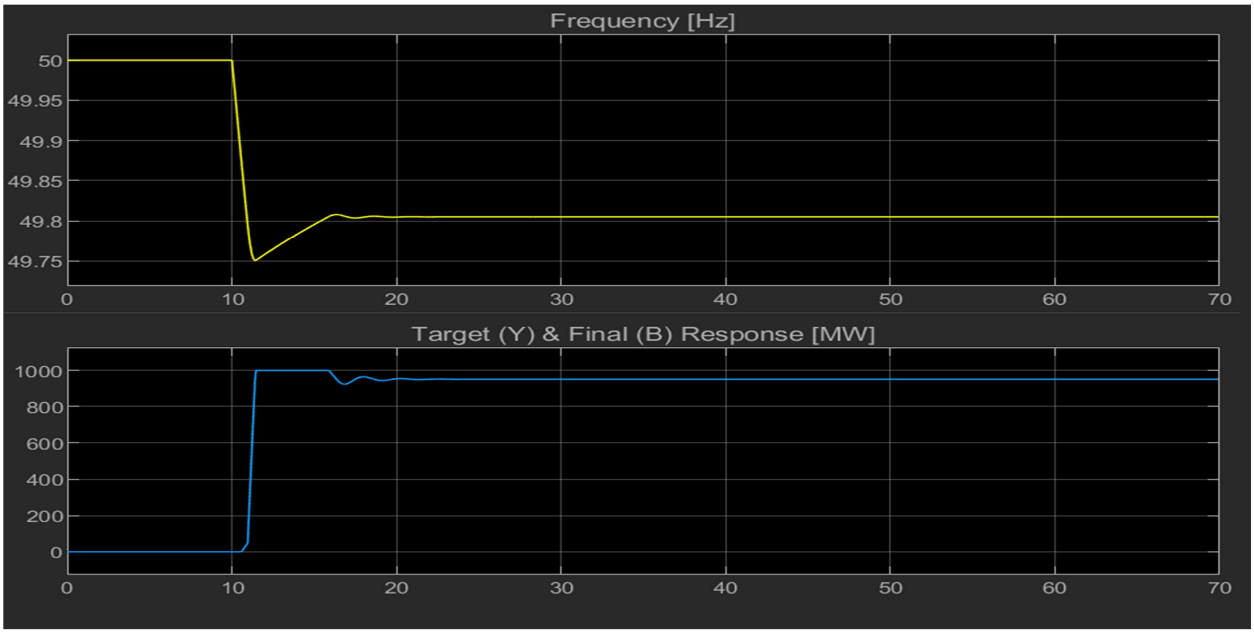

Figure 24: Simulink Output

11 DR

Simulation scenario parameters

- Loss: -1,000 MW

FRS parameters

- DR max volume: 1,000 MW
- Delay/lag: 2 s
- Ramp time: 8 s

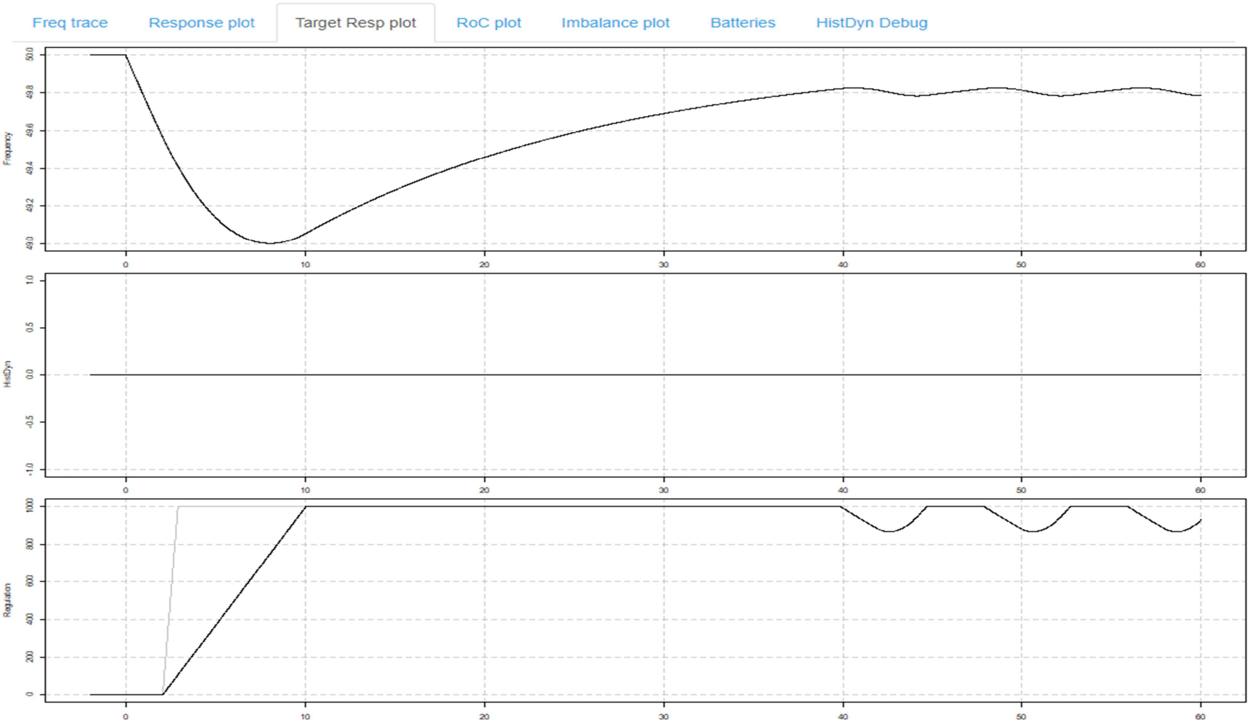

Figure 25: ShinyAppLegacy Output

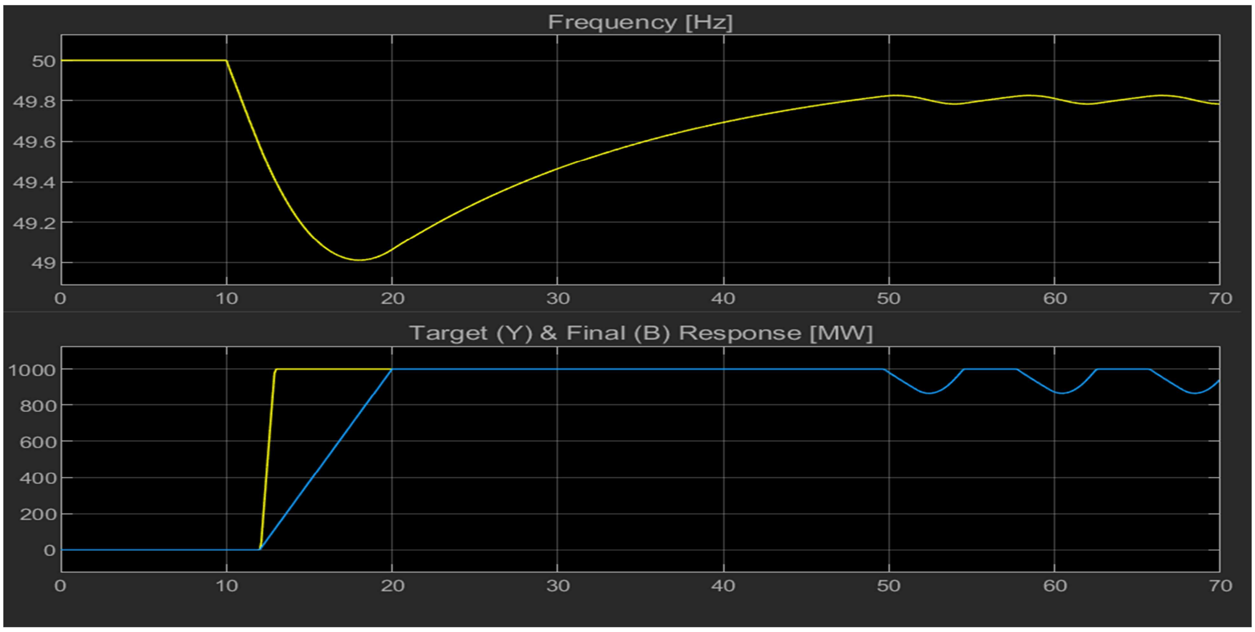

Figure 26: Simulink Output

12 RoCoF – Negative Loss

Combination of PSH Dynamic Response and RoCoF Trip with a negative Loss, i.e. loss of Generation.

Simulation scenario parameters

- Loss: -1,000 MW

PSH Dynamic Response parameters

- Max P Dynamic Response: 600 MW
- P delay/lag: 1.5 s
- P delivery time: 10 s
- S Dynamic Response: 1200 MW
- S delay/lag: 10 s
- S delivery time: 30 s

RoCoF Trip parameters

- RoCoF trip volume: -300 MW
- RoCoF limit: 0.1 Hz/s
- RoCoF delay/lag: 0.01 s
- RoCoF trig window time: 1.5 s

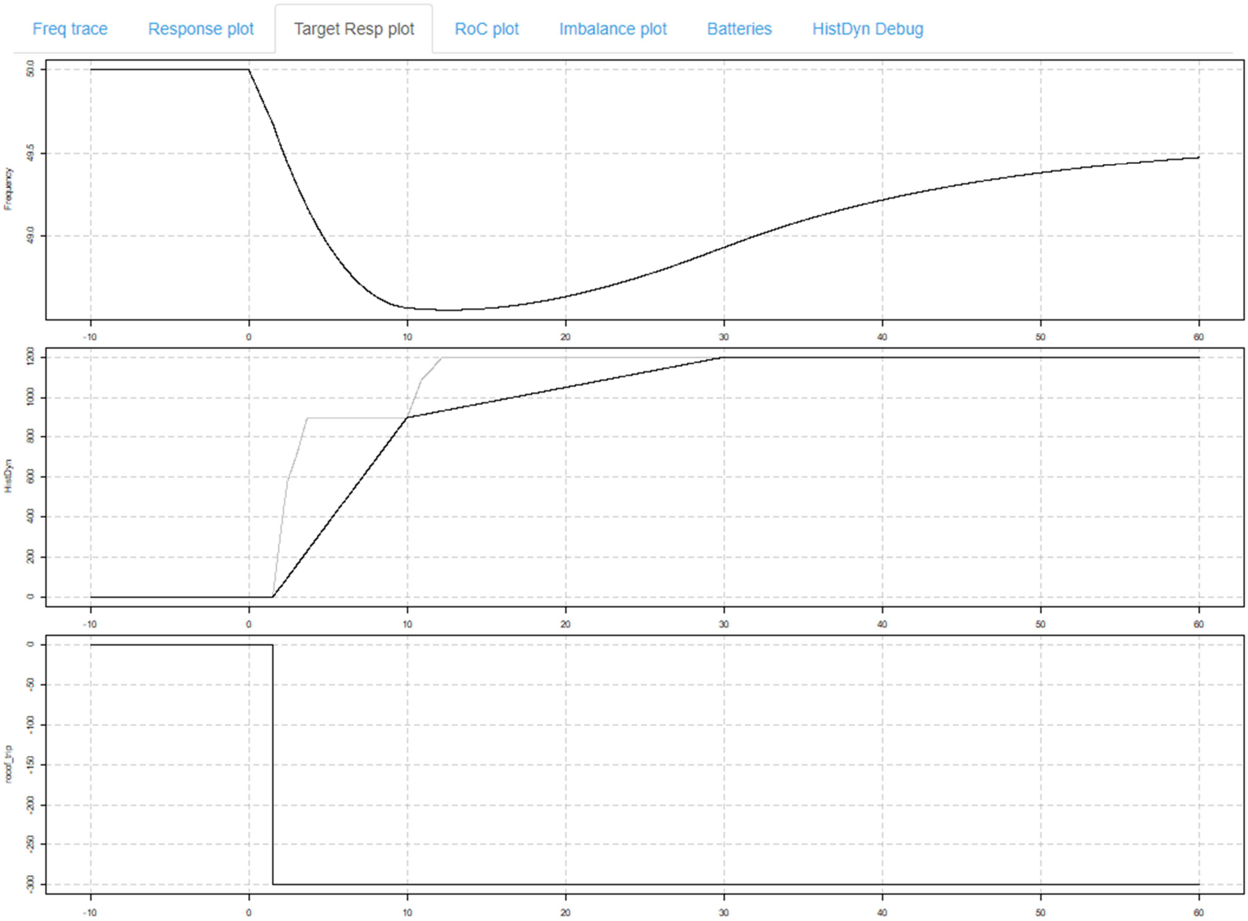

Figure 27: ShinyAppLegacy Output – Responses

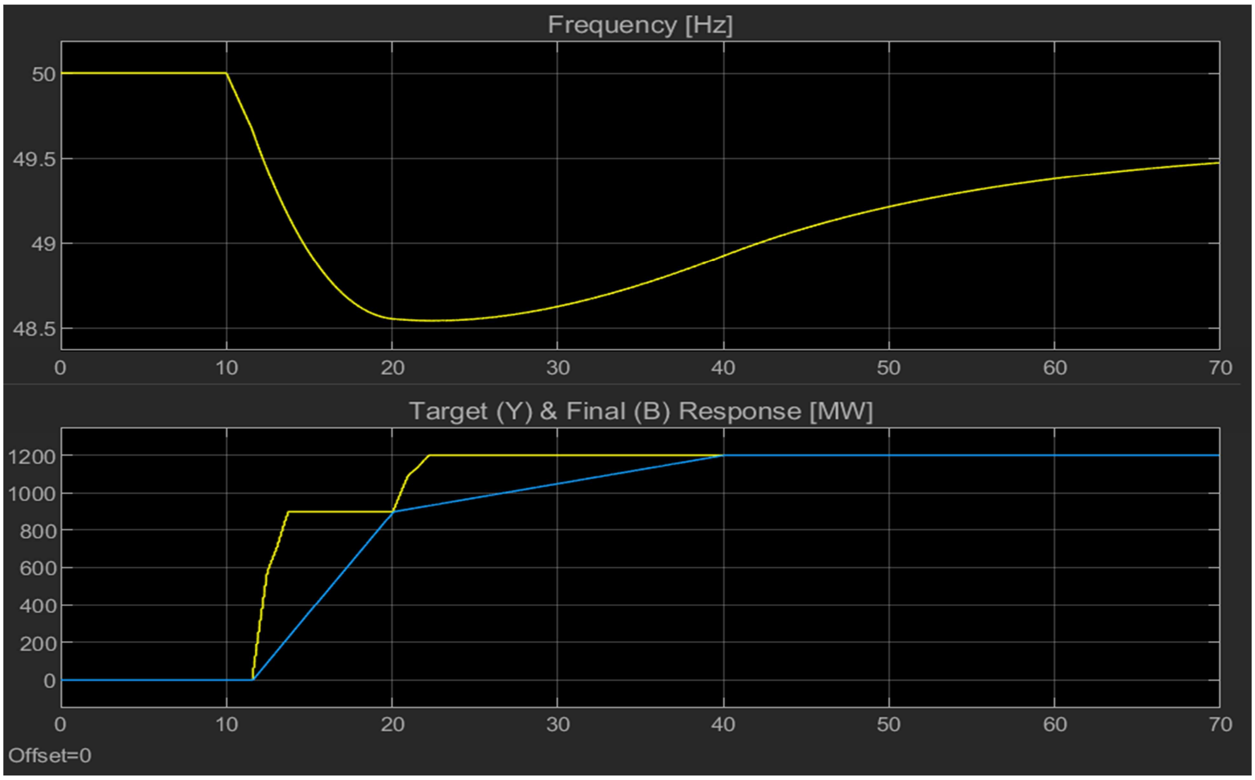

Figure 28: Simulink Output – PSH Dynamic Response

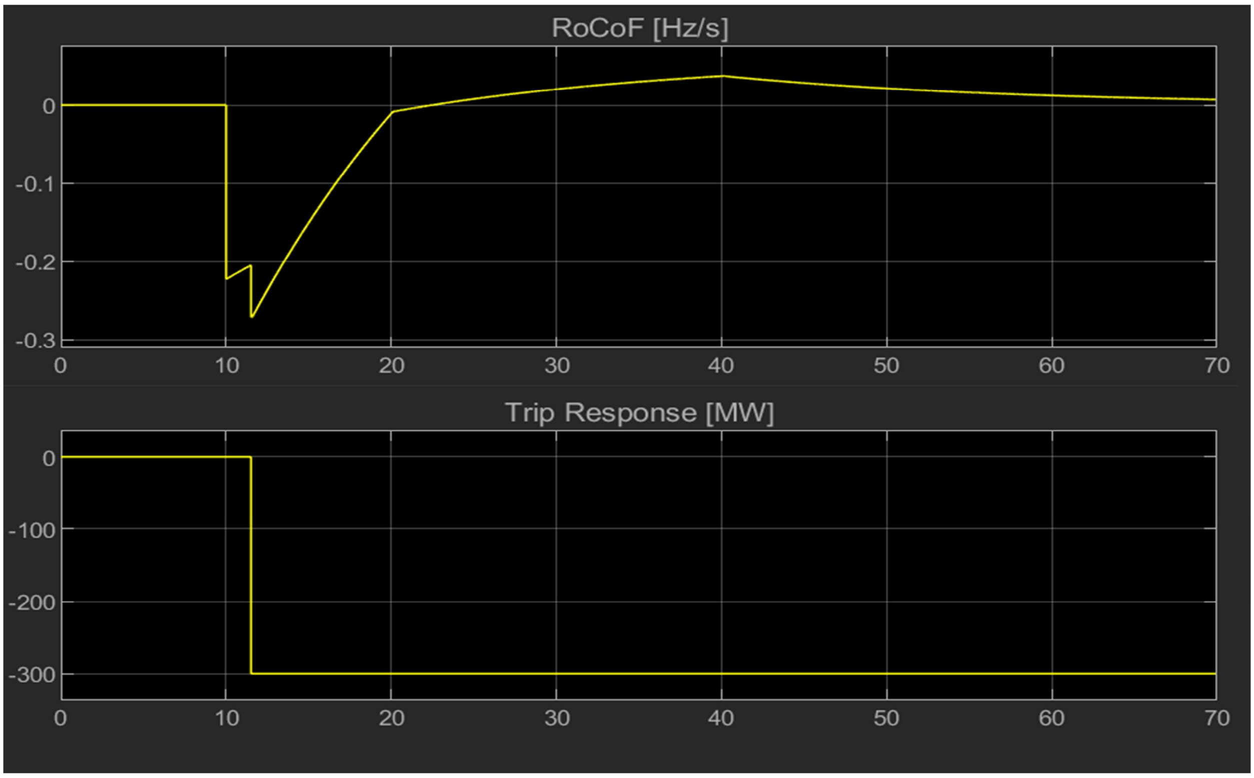

Figure 29: Simulink Output – RoCoF Trip

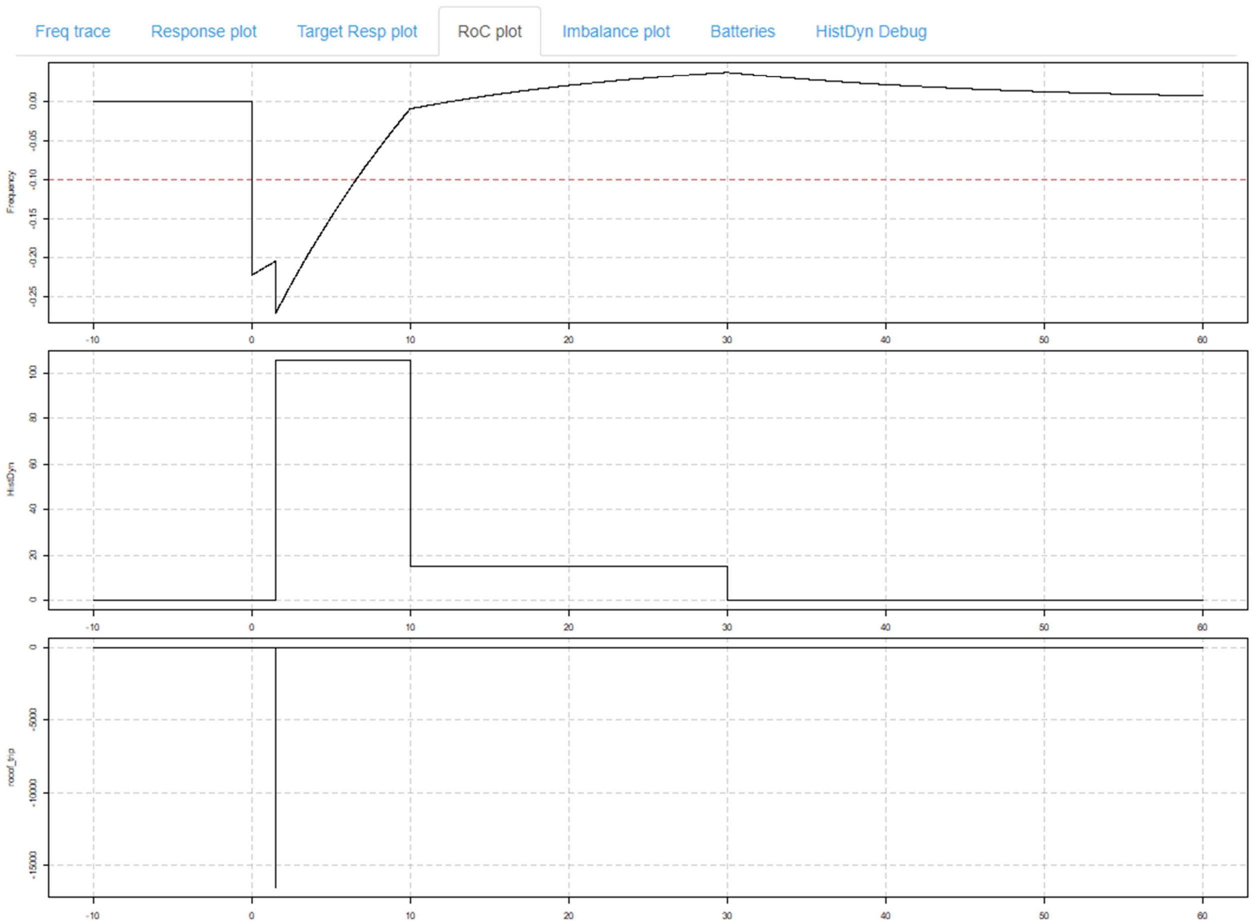

Figure 30: ShinyAppLegacy Output - RoCoF

13 RoCoF – Positive Loss

Combination of PSH Dynamic Response and RoCoF Trip with a positive Loss, i.e. loss of Demand.

Simulation scenario parameters

- Loss: 1,000 MW

PSH Dynamic Response parameters

- Max P Dynamic Response: 600 MW
- P delay/lag: 1.5 s
- P delivery time: 10 s
- S Dynamic Response: 1200 MW
- S delay/lag: 10 s
- S delivery time: 30 s

RoCoF Trip parameters

- RoCoF trip volume: -300 MW
- RoCoF limit: 0.1 Hz/s
- RoCoF delay/lag: 0.01 s
- RoCoF trig window time: 1.5 s

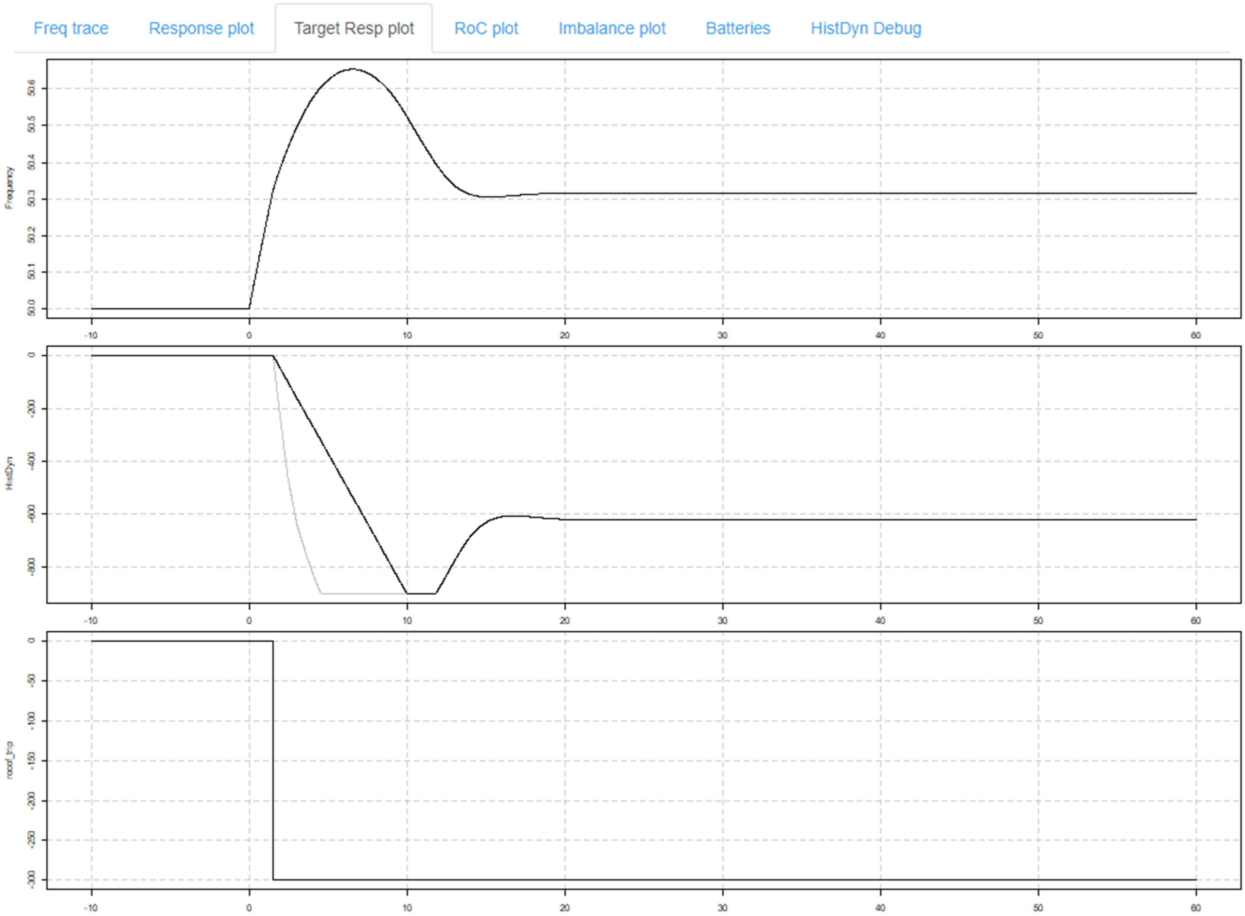

Figure 31: ShinyAppLegacy Output – Responses

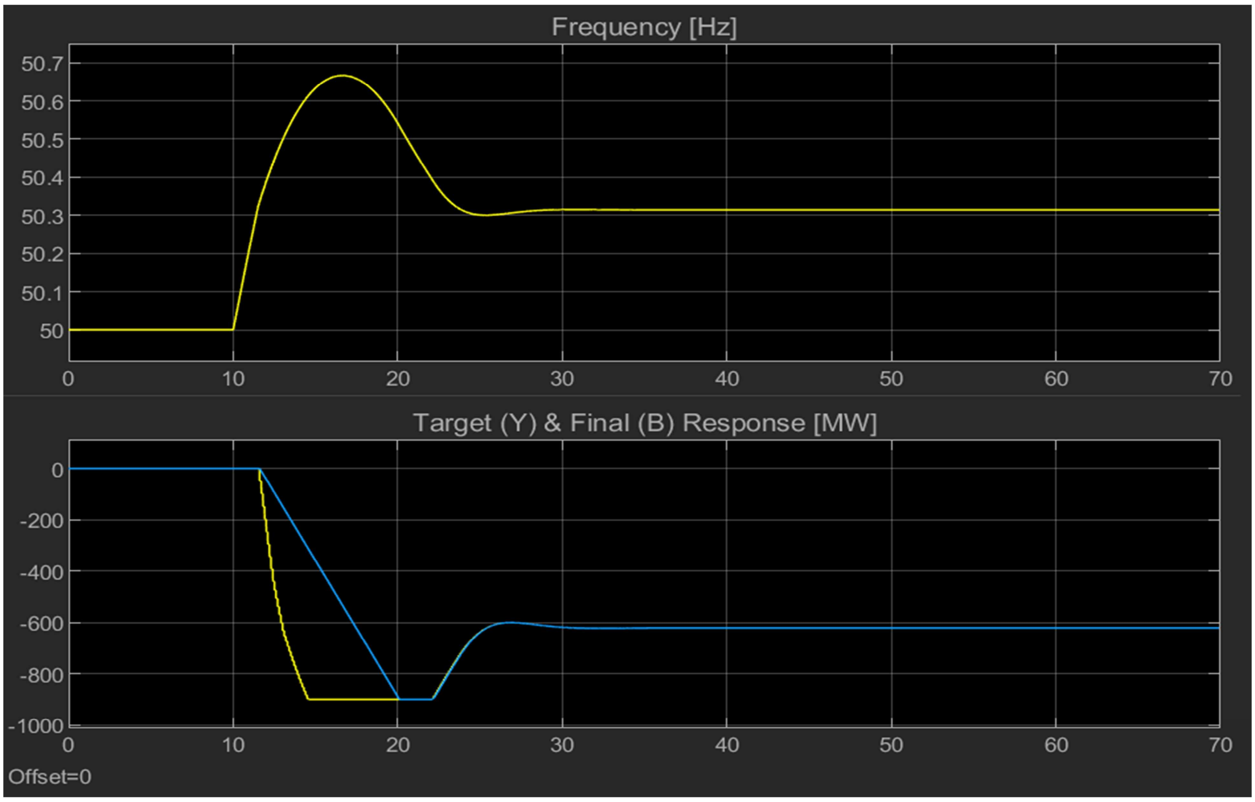

Figure 32: Simulink Output – PSH Dynamic Response

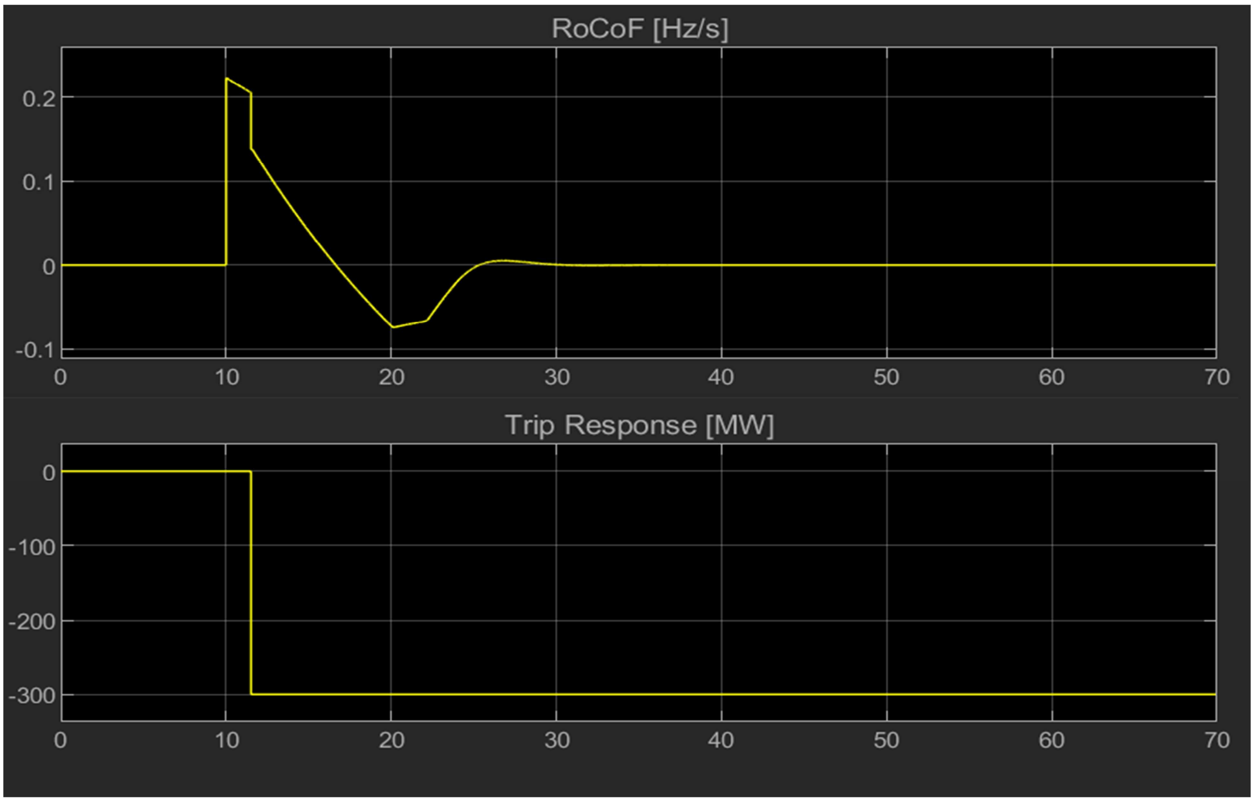

Figure 33: Simulink Output – RoCoF Trip

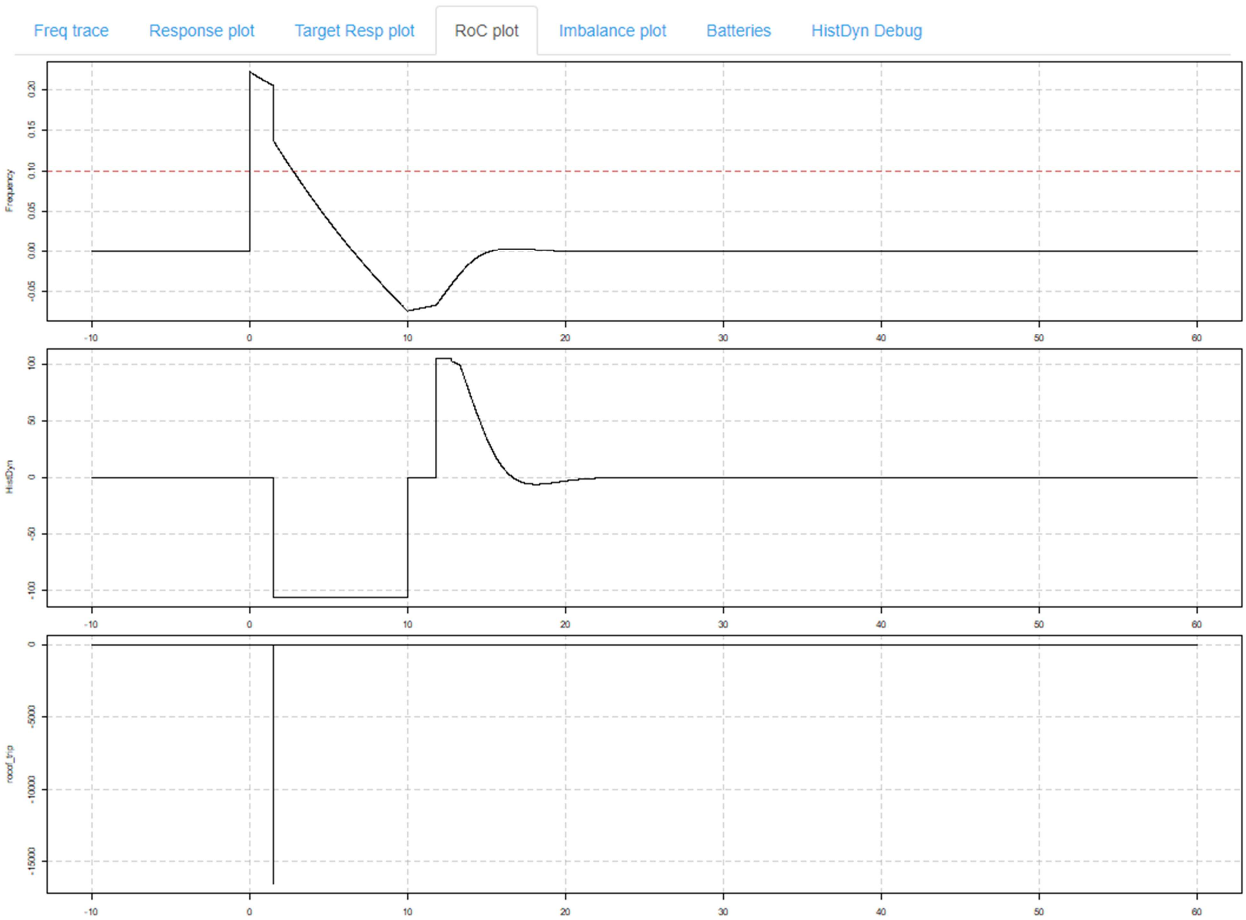

Figure 34: ShinyAppLegacy Output - RoCoF